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A wireless sensor network-based approach to large-scale dimensional metrology

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In many branches of industry, dimensional measurements have become an important part of the production cycle, in order to check product compliance with specifications. This task is not trivial especially when dealing with large-scale dimensional measurements: the bigger the measurement dimensions are, the harder is to achieve high accuracies. Nowadays, the problem can be handled using many metrological systems, based on different technologies (e.g. optical, mechanical, electromagnetic). Each of these systems is more or less adequate, depending upon measuring conditions, user's experience and skill, or other factors such as time, cost, accuracy and portability. This article focuses on a new possible approach to large-scale dimensional metrology based on wireless sensor networks. Advantages and drawbacks of such approach are analysed and deeply discussed. Then, the article briefly presents a recent prototype system – the Mobile Spatial Coordinate-Measuring System (MScMS-II) – which has been developed at the Industrial Metrology and Quality Laboratory of DISPEA – Politecnico di Torino. The system seems to be suitable for performing dimensional measurements of large-size objects (sizes on the order of several meters). Owing to its distributed nature, the system – based on a wireless network of optical devices – is portable, fully scalable with respect to dimensions and shapes and easily adaptable to different working environments. Preliminary results of experimental tests, aimed at evaluating system performance as well as research perspectives for further improvements, are discussed.

Keywords: dimensional metrology; large-scale metrology; large-volume metrology; coordinate-measuring systems; mobile measuring system; wireless sensor networks

1. Introduction

Owing to recent advances in integrated circuits and radio technologies, the use of distributed sensor networks is more and more widespread for a variety of applications, such as, environmental monitoring, indoor navigation, people and objects tracking, logistics, surveillance, industrial diagnostics and other activities. The facts of being typically composed by compact, lightweight and cheap devices make the wireless sensor networks (WSNs) appealing also for other possible uses. Among these, the field of dimensional metrology certainly offers a challenging and interesting scenario, especially when the dimensions to be measured are of the order of several metres (large-scale/large-volume dimensional metrology).

Nowadays, there are different instrumental solutions that allow performing dimensional measurements of large-size objects. In many cases, they are centralised systems where a single hardware unit is responsible for the measurements. Often, these instruments are unwieldy and hardly transportable and they usually show some coverage problems when dealing with complex working volumes (Peggs *et al.* 2009).

Recently, a few distributed solutions have been proposed, in which a set of metrological stations cooperates to measure the geometrical features of an object. These systems generally consist of a central unit to gather and elaborate data coming from a set of distributed sensor devices (Maisano *et al.* 2009). For this reason, they cannot be considered as completely distributed, even if they represent a valid attempt towards scalable and flexible systems.

Currently available systems for dimensional metrology applications are based on different technologies (e.g. optical, mechanical, electromagnetic and inertial), providing for several performance, operational, logistic and economic issues. Automation represents a key feature in an attempt to perform fast measurements with an easy-to-use instrument for possibly untrained operators (Ganci and Handley 1998).

This article presents a new concept of large-scale dimensional metrology based on WSNs. Although most of the existing systems rely on a centralised unit for measurement and/or data processing, the novelty of the proposed approach is based on the distributed nature of the measuring technology and its extended automation capabilities, involving hardware, software and process issues. This concept gets together flexibility and portability, characteristics of a distributed architecture, with capabilities of coordinated and cooperative control peculiar to intelligent WSNs. The embedded data elaboration hardware allows to partially share the overall computational load, thus providing for real-time measurement data processing. The software automation inheres availability of dimensional data as well as geometric features of the measured object, besides spatial coordinates of single points. This entails a reduction of required operator skills, being his/her duties limited to sensor carriage and/or data acquisition task management. In addition, process automation is implemented as to the setup's calibration phase and the data elaboration task. According to its working principles, the system is able to self-localise and characterise the remote sensing units, without needing any information concerning their technical specifications and spatial location/orientation. This aspect gives invaluable flexibility to the system as different sensor devices, having unknown characteristics, can be used in the same setup and contribute to the measurement process.

In order to analyse the feasibility of the proposed approach for performing dimensional measurements of large-size objects, a prototype – MScMS-II (Mobile Spatial coordinate Measuring System) – has been designed and experimentally tested, in terms of sensor device management, measurement data acquisition and achievable system performance.

In section 2, a background, inhering current available technologies for large-scale metrology (LSM), their working principles and configuration layout, is presented. Then the article focuses on the concept of distributed coordinate-measuring systems, in particular on the possible use of WSNs to this purpose. Advantages and drawbacks of distributed rather than centralised systems are analysed and discussed. Section 3 briefly introduces the prototype system MScMS-II. Preliminary experimental results, aimed at providing a metrological characterisation of the system, are discussed in section 3 as well. Finally, section 4 reports some concluding remarks and proposes future research developments.

2. Large-scale dimensional metrology

Dimensional metrology is the branch of metrology that deals with measurements of geometrical features. LSM, in particular, can be defined as 'the metrology of objects in which the linear dimensions range from tens to hundreds of meters' (Puttock 1978). LSM includes a wide range of applications, such as dimensional measurements of large structures, monitoring of deformations, alignment procedures in manufacture assembling, in many different industrial sectors, such as aerospace, railway and shipbuilding. The large number of existing metrological solutions can be classified according to different criteria, including measuring technologies, working principles, measurement procedures and system architectures.

Although a wide variety of technologies has been implemented for dimensional metrology applications, at present, optical-based systems are largely used due to their advantages over the other approaches as to metrological performance and their potentialities for LSM applications. A taxonomy of main existing LSM solutions is reported in Table 1, referring to measurement procedures (contact and non-contact instruments), working principles (multiple lengths, one length and two angles and multiple angles) and system architectures (centralised and distributed).

According to measurement procedures, a classification has been proposed in Maisano *et al.* (2009),

Table 1. Taxonomy of available solutions for metrology applications.

		SYSTEM ARCHITECTURE	
MEASUREMENT PROCEDURE	WORKING PRINCIPLE	*Centralized*	*Distributed*
Contact	*Multiple lengths*	CMMs	ToF-based systems TDoF-based systems
	Two angles and one length	Laser trackers Total stations	
	Multiple angles	Single/stereo camera based systems	iGPS Hi-Ball Multi camera based systems
Non-contact	*Multiple lengths*	Tacheometers	
	Two angles and one length	Theodolites Laser radars	
	Multiple angles	Digital fringe projection systems Single/stereo camera based systems	Multi camera based systems

distinguishing between contact and non-contact instruments. Contact systems perform measurements by touching the workpiece, either through a mechanical arm or through a portable probe. On the contrary, non-contact systems do not need to touch the object to be measured.

A further categorisation of the available instruments has been reported in Cuypers *et al.* (2009), referring to their working principles. Three groups have been identified, depending on whether they perform measurements by using multiple lengths, one length and two angles or multiple angles. The former method, first used by the well-known coordinate-measuring machines (CMMs) to evaluate the position of its remotely controlled contact probe by knowing the probe geometry and the distances from the three reference axes along which it moves, is common to the systems implementing a multilateration approach as well. More specifically, these techniques use the known locations of three or more reference points, and the measured distance between the point to be localised and each reference point. The unknown coordinates can be found by solving a nonlinear optimisation problem (Franceschini *et al.* 2009a). This approach is very similar to GPS (global positioning system) localisation principle (Hofmann-Wellenhof *et al.* 1997). Multilateration principles are used by the measurement systems based on laser interferometers (Cuypers *et al.* 2009) as well as by those based on ToF (time of flight) or TDoF (time difference of flight) (Franceschini *et al.* 2009a). On the other hand, many coordinate-measuring systems rely on the determination of one length and two angles. These systems, also called spherical coordinate-measurement systems, locate a point with reference to a spherical coordinate system. Examples of such systems are laser trackers, laser radars and total stations (Cuypers *et al.* 2009).

Finally, instead of using two angles and a distance measurement, it is possible to evaluate the position of a point in a three-dimensional (3D) space using angular information from two or more reference points. This approach relies on the well-known triangulation principle, which uses the known locations of two or more reference points and the relative measured angles between the point to be localised and each reference point (Doğançay 2005). All camera-based systems (Mikhail *et al.* 2001) as well as the indoor-GPS (iGPS) (ARC Second 2010) rely on this working principle.

In the last decade, many new large-scale dimensional metrology systems have been designed and proposed (Peggs *et al.* 2009). In particular, some of them – composed by several distributed components – arouse a certain interest because of their unique features of flexibility and scalability (Maisano *et al.* 2009). In general, according to their architecture, dimensional metrology systems can be classified into two groups (see Table 1):

- Centralised systems. A centralised system is essentially a standalone unit, which works independently from other external devices to perform dimensional measurements. Often the centralised unit is difficult to move and its working volume is inevitably limited by the technology used. Laser trackers (Automated Precision 2009, Faro Technologies 2009, Leica Geosystems 2009), laser radars (Leica Geosystems 2009), theodolites and optical CMMs (Axios 3D 2009, Metronor 2009, Northern Digital 2009, Nikon Metrology 2010) represent widely known examples of metrological instruments based on a centralised approach.
- Distributed systems. These systems generally consist of a set of remotely distributed devices and a central processing unit, which is in charge of data acquisition and post-processing elaboration to provide measurement results. According to the level of interaction of network devices, a further distinction can be made between the following categories:
    - Semi-distributed systems: The distributed approach is limited to the spatial location of the devices, which are just remote sensing units, providing reference points in the 3D space. They are unable to communicate with one another and to adaptively reconfigure their sensing task. The iGPS (Nikon Metrology 2010) and the V-Star system (Geodetic Services 2010) are representative examples of such a category;
    - Fully distributed systems: Similar to the semi-distributed ones, these systems are characterised by a distributed hardware architecture. In this case, however, the remote sensing devices are intelligent agents, i.e. autonomous entities, which cooperate and coordinate their activities to achieve the common objective of performing the measurement. Owing to their nature, these systems may be organised according to a flat structure (each node is linked to the central unit) or a hierarchical structure (clusters of nodes are in charge of more powerful cluster nodes) (Cassandras and Li 2005).

It has to be observed that, up to now, even if many noteworthy efforts have been directed towards the realisation of distributed systems, a real fully distributed system has still to come.

2.1. *Distributed dimensional metrology systems*

2.1.1. *State-of-the-art*

The history of distributed LSM systems is quite short and dates back to the last few years (Peggs *et al*. 2009). Nevertheless, a few systems – relying on different technologies and working principles – have already been proposed (Maisano *et al*. 2009).

The iGPS (Nikon Metrology 2010) uses a number of distributed transmitters equipped with two rotating laser beams and an infrared (IR) light to determine the relative angles from the transmitters to the photodiodes sensors embedded in a mobile hand-held probe (ARC Second 2010) (see Figure 1).

According to the known location of the transmitters, which is normally obtained in an initial setup phase, the position of the mobile probe can be calculated (Ferri *et al*. 2010). An experimental characterisation of iGPS operational performance and a comparison to those of a laser tracker has been reported in Wang *et al*. (2008), referring to a real working environment. Whereas the distributed system demonstrated high repeatability, measurement uncertainty resulted to be consistently affected by working volume size and environmental factors.

A similar system is the HiBall (3rdTech 2010). It consists of two key integrated components: a mobile probe equipped with lenses and photodiodes and a set of IR Light Emitting Diodes (LEDs), generally mounted on the ceiling of the working environment. The mobile probe is able to estimate the angular position of the LEDs with respect to its local reference system. The position of the probe is thus found by triangulation knowing the locations of the LEDs (Welch *et al*. 2001).

Developments in imaging technology, which afforded the community large-area Charge-coupled Device (CCD) sensors and improvements of target image location algorithms, have led to an ever-increasing competitiveness of vision-based metrology. As a matter of fact, different well-settled solutions based on photogrammetry are commercially available, providing for accurate, portable and versatile instruments for 3D coordinate-measurement (Optitrack 2009, Vicon 2009, Geodetic Services 2010). The fundamental principle used by photogrammetry is triangulation (Mikhail 2001). By taking photographs or video images from at least two different positions, it is possible to reconstruct the spatial location of a point and, therefore, the geometry or the main features of an object. Notwithstanding their multiple sensor-based structure, the existing photogrammetric instruments are applied to reduced working volumes and do not exploit the potentialities of a WSN layout.

Generally speaking, although the systems so far described present a physically distributed layout, their distributed components do not possess any kind of 'intelligence', computational capability or coordination potentiality.

2.1.2. *Appeal and drawbacks*

The appeal of distributed systems derives from many features that make them different from conventional centralised systems:

- Flexibility. As they consist of multiple remote sensors, distributed systems can be easily arranged in the working volume according to the user needs, the environment geometry and the measurement task. System flexibility can be further enhanced by implementing pre-processing software tools providing possible

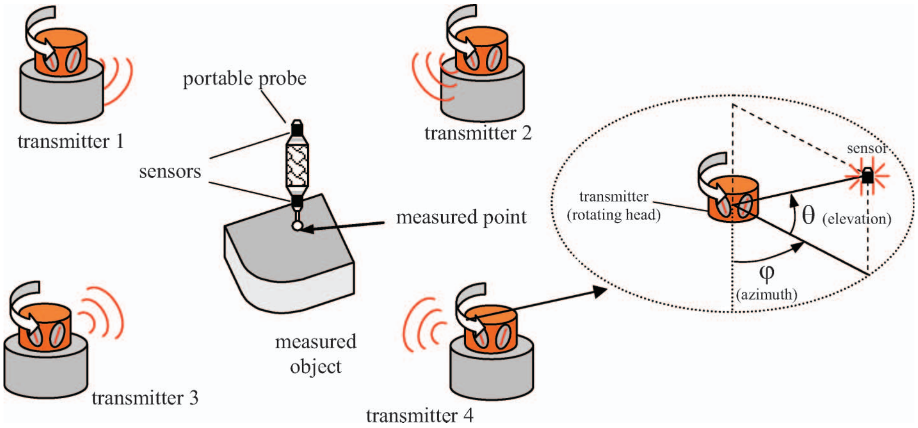


Figure 1. Working principle of the iGPS. To obtain accurate angle measurements, the iGPS uses rotating laser beams (ARC Second, 2010). Knowing the azimuth and elevation angles (φ, θ) from two or more transmitters, the system univocally determines the position of a probe.

configuration layout, aimed at optimising the metrological performance and/or the measurement volume (Franceschini *et al.* 2008, Galetto and Pralio 2010). The sensor placement problem, intended as the problem of positioning and orienting a set of sensors in an attempt to cover a measurement region, has been extensively faced referring to different sensing technologies and fields of application (Younis and Akkaya 2008). Optimal camera placement issues have been treated in Mason (1997) and Olague and Mohr (2002) with reference to accurate 3D measurements through photogrammetric systems. The problem of determining sighting and positioning strategies for fringe projection sensors is tackled in Weckenmann *et al.* (2008), to provide assistance to the operator dealing with a multi-sensors system. The next best view problem is faced in Munkelt *et al.* (2009) as the problem of planning sensor positions for a 3D reconstruction task using time-of-flight camera data. On the other hand, the configuration design issue has been approached also in Ray and Mahajan (2002) and Laguna *et al.* (2009) for positioning ultrasonic devices for indoor localisation and navigation of autonomous vehicles. Adaptive sensor placement strategies (Bulusu *et al.* 2001) could represent a viable way to provide capabilities to add or remove sensing units according to the user needs, making these systems extremely flexible as to their implementation for industrial applications.

- Redundancy. In typical working conditions, distributed systems are often able to refer to more distributed components than strictly needed. Depending on the localisation technique adopted, information redundancy enhances system accuracy and gives the system the possibility of implementing real-time verification strategies (Franceschini *et al.* 2009b).
- Reliability. Reliability is the ability of a system to perform and maintain its functions in routine circumstances, as well as hostile or unexpected circumstances. A survey of fault tolerance issues in sensor networks is given in Koushanfar *et al.* (2004), including techniques for detection and diagnosis. Research work is focused both on sensor deployment strategies providing fault tolerance against node failures (Hao *et al.* 2004; Bredin *et al.* 2005; Han *et al.* 2007) and fault-tolerant algorithms for detecting and localising targets in networks with faulty nodes (Ding *et al.* 2007). Similarly, if one or more remote devices are not working properly, distributed metrology systems, as generally characterised by hardware redundancy, can actually use the 'healthy' nodes to compensate the malfunctioning of a part of the network.
- Scalability. The major strong point of a distributed system is the capability to easily adapt to large dimensions and unusual shapes. The real working volume of a distributed metrology system is related to the network layout. Changing density and/or position of the remote sensing units, the user can size and shape the working volume, within the network design phase as well as during the experimental campaign.
- Concurrent measurement capability. Distributed metrology systems generally allow the use of different measurement tools (multiple targets and/or mobile probes) at the same time. Once the system infrastructure has been set up, an unlimited number of tools can actually operate within the workspace, without any additional cost per user.
- Sensor fusion. A wide variety of sensor data fusion applications have been proposed in literature, considering heterogeneous sensors, spatially distributed sensors and asynchronously sampled sensors. The use of heterogeneous sensors, i.e. sensors measuring different physical entities, entails accurate models for correlating sensor observations. Moreover, the possibly distributed sensor architecture requires modelling how the observations depend on sensor positioning. On the other hand, a modelling of the time evolution of the measured parameters is needed whenever asynchronous sampling of sensors is performed. Therefore, a modular architecture could give the opportunity to integrate the metrological system with other spatially distributed sensors (in order to monitor temperature, humidity, vibrations, light intensity, etc.) (Akyildiz *et al.* 2007). The sensor data fusion, intended as the processing and elaboration of data from heterogeneous sensors, provides capabilities to perform an environmental mapping of the working volume and to monitor the operating conditions of the dimensional measuring devices. Moreover, multi-resolution systems can be integrated to provide different granularity in data acquisition.
- Line-of-sight. The distributed nature of the configuration layout and the sensor redundancy better face with 'visibility' problems, such as shadowing, line-of-sight obstructions and signal reflections.

On the other hand, contrary to centralised systems that are made by a single metrological unit, the distributed nature of the described systems requires the coordination and management of multiple stations. The major disadvantages of these systems are as follows:

- Setup. To work properly, every distributed system needs to know several parameters of the local hardware. Some of these parameters may change either because of environmental factors (e.g. vibrations, temperature or humidity changes), or due to unpredictable reasons (such as accidental movements of network nodes). Errors during the setup phase adversely affect the accuracy of the measurements (Mastrogiacomo and Maisano 2010). To achieve the optimum accuracy, each distributed system generally needs a careful setup phase. During this phase, which can be automated to some extent, the system calculates information like positions and orientations of components, local temperatures, humidity, pressure and so on. This information is useful during the measurement.
- Expertise. Distributed metrology systems are typically less user friendly than centralised systems. They generally need a more experienced and careful user, especially during the setup process. Because they consist of multiple stations, particular attention has to be paid to coordinate the data acquisition from different sensing devices (e.g. sensor device synchronisation).
- Standards. While these new systems are attractive to potential end-users, standards, best practice methods and independent performance verification techniques are usually not available (Peggs *et al*. 2009).
- Accuracy. The performance of distributed metrology systems is strongly related to several factors that can affect the accuracy of the system adversely, such as the number of network devices, the setup parameters and the network geometry with respect to the spatial distribution of measurement points.

2.2. *WSN–based approach*

WSNs are typically composed of small and lightweight devices that can be easily deployed and arranged in a working environment. Furthermore, each device is generally provided with both communication and computation capabilities given by the embedded electronic components (Akyildiz *et al*. 2002). These features certainly increase the appeal of WSNs and make them suitable for the design of a fully distributed system. Recently, the attention has been focused on the integration of video devices with scalar sensors, to setup networks of wirelessly interconnected devices able to fuse multimedia data from heterogeneous sources. Comprehensive surveys on wireless multimedia sensor networks and their applications and testbeds are available in Akyildiz *et al*. (2007, 2008).

Besides existing application fields, such as tracking, home automation, environmental monitoring and industrial process control, the distributed network-based layout has been more recently implemented also in dimensional metrology applications (e.g. Nikon Metrology 2010, 3rdTech 2010). Accordingly, measurement systems based on spatially distributed sensing units demonstrate profitable scalability features. As a matter of fact, their modular architecture makes them suitable for LSM, overcoming limitations of existing digital photogrammetry-based systems. Real-time image acquisition of different targets, possibly located in different regions of the working volume, is then possible by spreading around the sensor devices, provided that the acquisition task is synchronised and a common reference system is given. These capabilities make the proposed system a feasible solution for tracking mobile objects, even if characterised by fast dynamics. This property is particularly interesting in an attempt to automate the contact measurement procedure. Most of the commercially available instruments provide an accessory hand-held probe for touching the reference measurement points (Automated Precision 2009, Axios 3D 2009, Leica Geosystems 2009, Nikon Metrology 2010), thus involving a direct interaction between the sensor equipment and the human operator besides a strong dependence on his/her skills. An alternative approach, proposed in Franceschini *et al*. (2009d), relies on autonomous unmanned platforms for carrying the sensor equipment and moving the contact probe around the working volume. According to this new perspective, the human role should be scaled down to simply manage the task-related issues, such as type of measurement (e.g. dimensional measurement, geometry reconstruction and single point verification) and data acquisition procedures (e.g. point sequences, repeated sampling), and remotely monitor the unmanned platform that should autonomously perform the measurement. This approach clearly shows the need for a flexible system architecture that is able to provide measurement data for control as well as metrological issues.

As described in section 2, currently available dimensional metrology systems rely either on distance or angle measurements. Thus, the possible use of a WSN-based system for dimensional metrology applications is certainly bounded by its capabilities of performing such kind of measurements. Nowadays, there are many approaches to this field, relying on different technologies and sensors. Angular measurements can be achieved, for example, using accelerometers, magnetometers, gyroscopes, CCD sensors, photodiodes or simply measuring the difference in the received phase of a radio signal at each element of an antenna array (Kwakkernaat *et al.* 2008). On the other hand, distance measurements can be obtained, for instance, evaluating the ToF of a particular signal (such as an ultrasound signal), the time difference of arrival of different signals or the received strength of a radio communication signal (Franceschini *et al.* 2009c).

Whatever the system components and the localisation algorithms are, a WSN-based metrology system represents a further step towards hardware and software automation in dimensional measurement applications. Owing to its capabilities of sharing the metrology task, each network device could work cooperatively with the aim of determining the geometrical features of an object. In this way, the measurement results to be the synthesis of the information locally gathered and shared by each network node. Communication links among the network nodes also provide capabilities to possibly reconfigure their orientation during the task according to measurement conditions and procedures, aiming at optimising the overall system performance.

3. System prototype implementation

The MScMS-II – developed at the Industrial Metrology and Quality Engineering Laboratory of DISPEA, Politecnico di Torino – is an indoor coordinate-measuring system based on IR optical technology and designed for LSM applications. As a first prototype, it implements both distributed and centralised logics. Its architecture consists of three basic units:

- a sensor network of optical devices, suitably distributed within the measurement volume;
- a mobile wireless and armless probe, equipped with two reflective markers, to 'touch' the measurement points;
- a central unit, connected via an antenna linked to the WSN, to acquire and elaborate the data sent by each network node.

The network of spatially distributed optical sensors is aimed at providing reference points for locating the portable probe, by establishing visual links with the markers that are visible in the camera 'viewing volumes'. The probing point, i.e. the point of the probe tip contacting the workpiece, is then calculated according to the reconstructed positions of markers' centres and the *a priori* known probe geometry. An earlier prototype of MScMS exploited ultrasonic (US) transceivers to communicate and evaluate mutual distances between the distributed sensor nodes and the hand-held probe (Franceschini *et al.* 2009a). The poor characteristics of US devices (e.g. non punctiform dimensions, speed of sound dependence on operating temperature, wave reflection and diffraction) caused a low accuracy in the measurement results (Franceschini *et al.* 2009a,b). To enhance system performance, current version implements an IR-based optical outside-in system, estimating the position of passive retro-reflective markers from their projections in different camera views (Galetto *et al.* 2009).

The system is characterised by a fast acquisition and measurement procedure, being the acquisition task related to camera frame rates, and the measurement task dependent on the number of points and the processor used. System portability strongly depends on modular architecture, which shares sensing and computational capabilities among several remote units of reduced size and weight. The system can then be easily transportable and objects can be measured in place. Setup takes just a few minutes, as no warm-up times are required for the sensing units. The camera self-calibration, based on a collection of images of a single reflective marker, randomly moved in several unknown positions within the working volume, requires a few minutes, including data gathering and elaboration tasks.

3.1. *Wireless sensor network*

Currently, the distributed network of the MScMS-II prototype has been set up by using low-cost commercial IR cameras, characterised by an interpolated resolution of 1024 × 768 pixels (native resolution is 128 × 96 pixels), a maximum sample rate of 100 Hz and a field-of-view (FoV) of approximately $45^\circ \times 30^\circ$. Graphical representations of a single camera viewing volume and the coverage volume of a set of sensors are reported in Figures 2 and 3, respectively. Each camera implements a real-time multi-object tracking engine, allowing to track up to four IR light sources. To work with passive markers, each camera is coupled with a near-IR light source (Figure 4), consisting of a 160-chip LED array with a peak wavelength of 940 nm and a viewing half-angle of approximately 80°. The overall sensor set (camera and LED array) weights less than 500 g and is about 13 × 13 × 15 cm size. Because marker dimensions, camera resolution, IR light source power and working volume are strictly related parameters, the IR sensor sensitivity has been experimentally evaluated by testing the visibility distance of differently sized retro-reflective spheres (see Figure 2). Referring to the used IR technology, the system

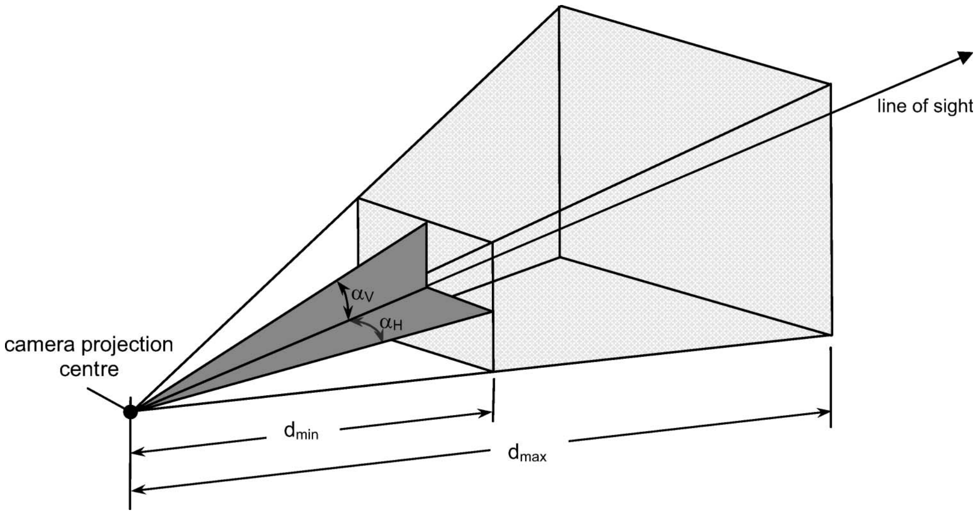


Figure 2. Graphical representation of the sensitivity range of the IR camera. The vertical and horizontal view angles are indicated as α_V and α_H, respectively. They identify the camera FOV. The light grey volume represents the camera viewing volume, within which a reflective marker is visible and traceable.

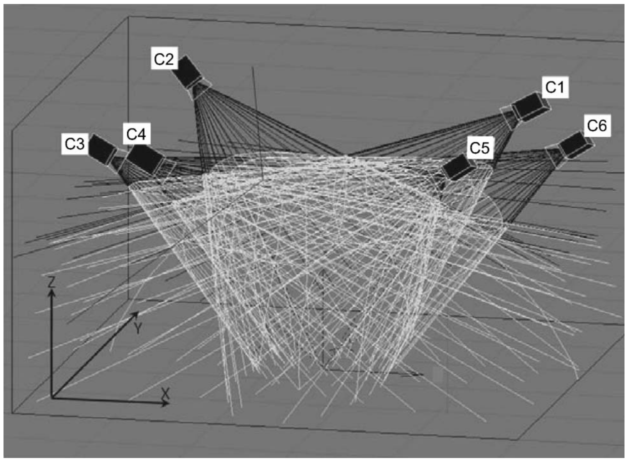


Figure 3. Graphical representation of the working layout. The dark grey regions represent the ideal viewing volume of each camera. The light grey region identifies the coverage volume, i.e. the volume wherein it is possible to reconstruct the 3D position of a marker. It has to be noted that, according to triangulation principles, the coverage volume has been referred as the volume of intersection of at least two viewing volumes.

demonstrated to be able to track a 16-mm diameter marker in a range between $d_{min} = 50$ mm and d_{max} 3500 mm. On the other hand, by using a 40-mm diameter marker the traceability ranges from 300 to 6000 mm. Although the upper bound (d_{max}) of this range represents a limitation in terms of marker visibility in the camera image plane, the lower bound (d_{min}) represents the distance under which the tracking engine is unable to correctly find the centre of the point projection in its view plane.

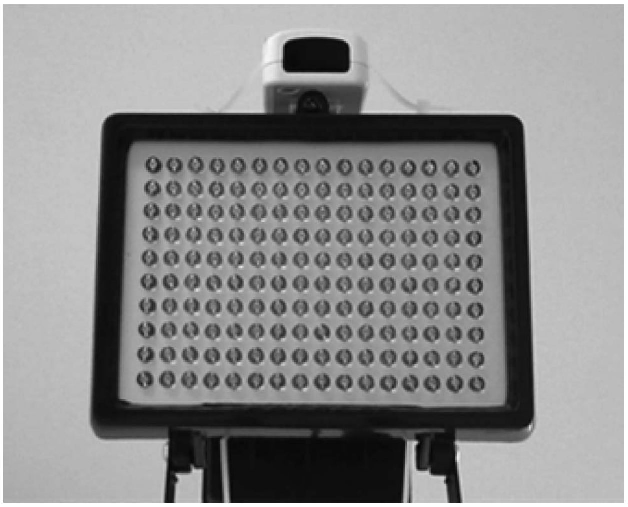


Figure 4. Main components of the IR-based sensor network: an IR camera is coupled with an IR LED array to locate passive retro-reflective targets.

Besides the camera, each network device is provided with an accelerometer used for diagnostic purposes (i.e. to detect possible movements or vibrations changing the calibrated positions).

It has to be noted that part of the data elaboration task is locally performed by the remote sensing units. In detail, wireless network devices are in charge of the following:

- Image processing. To save computational capabilities and to reduce the radio communication loads, all images acquired by the wireless devices

are processed onboard. Each device implements a real-time tracking engine, allowing tracking up the brightest IR sources in the camera field of view and thus providing to the central unit their 2D position coordinates.
- Image filtering. To prevent noisy measurements and undesired reflections, the network devices only track IR sources with brightness larger than a certain threshold that is empirically established. No filtering on the shape of the light sources is performed.

As a matter of fact, the embedded real-time tracking and filtering capabilities of the distributed remote sensing devices save the computational effort for performing the image analysis and spot coordinates identification by the central unit.

3.2. *Measuring probe*

The mobile hand-held probe (Figure 5) consists of a rod, equipped with two reflective markers at the extremes and a calibrated tip to physically 'touch' the measurement points. Reflective markers have been made by wrapping a retro-reflective silver transfer film around polystyrene spheres.

Referring to Figure 5, spatial coordinates of point V can be easily determined, knowing the positions of the two marker centres and the geometry of the probe, through a linear equation (Franceschini *et al*. 2009a, Galetto *et al*. 2009). A correction algorithm, taking into account the probe trajectory when approaching the measurement point, has been implemented. To this end, the central processing unit stores the time history of the reconstructed spatial coordinates of the probe markers. The probe trajectory in a predefined time interval before the measurement is thus reconstructed and used to correct the coordinates of the probe tip.

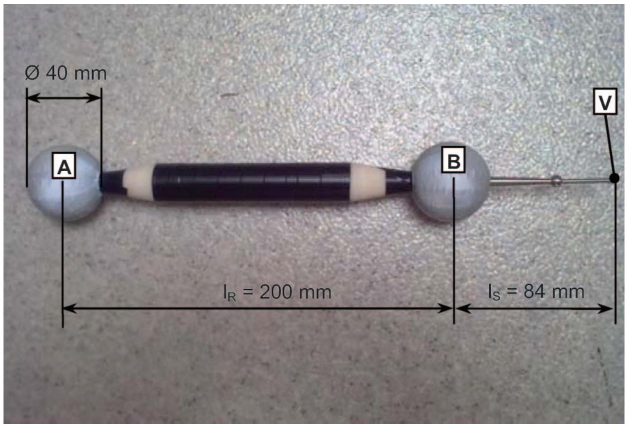


Figure 5. Mobile hand-held measuring probe.

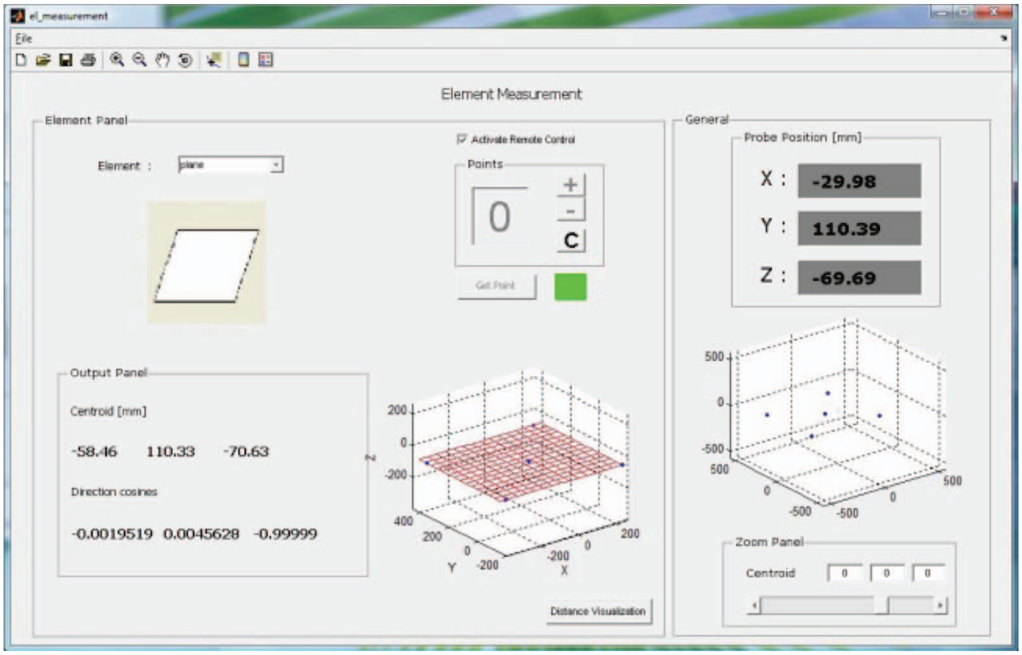
3.3. *Central unit*

The central unit consists of a PC equipped with an Intel Quad Core Q9300 (4 × 2.5 GHz) CPU and 4GB DDR 2 RAM. The PC is connected to the WSN devices via a radio link.

The central unit is currently used both for data processing and visualisation. The centralised unit is in charge for the following tasks:

- Synchronisation. According to the radio communication link, cameras are sequentially sampled. This introduces a delay between the acquisition time of images from different cameras. On the other hand, the onboard image processing lightens the communication load, thus reducing the acquisition delay to a minimum.
- Camera calibration. A camera calibration procedure has to be carried to provide to the triangulation algorithm the spatial coordinates of the reference points, i.e. the IR sensor devices. The multi-camera calibration problem is faced by using a fully automatic technique of self-calibration (Svoboda *et al*. 2005). This method is able to reconstruct camera internal parameters besides its positions and orientations. It requires a minimum of three cameras and a calibrated artefact to align and scale the reference system.
- Localisation. According to the 2D coordinates of the IR spot(s) provided by each camera, the central unit reconstructs the 3D position of any marker by applying triangulation algorithms (Hartley and Zisserman 2004).
- Pre-processing. The central unit is able to run pre-processing software tools to provide an optimal WSN configuration, taking into account the metrology task, the geometry and shape of the measurand and the working environment layout.
- Diagnostics. The central unit is responsible for running diagnostic algorithms, reporting possible malfunctions of the sensor devices.

These functions have been implemented into *ad hoc* developed software, providing a comprehensive and user-friendly graphical interface for managing the measurement tasks (Figure 6). Network design and calibration, marker localisation as well as dimensional measurement tasks are managed through different applets. As a matter of fact, spatial coordinates of single points, dimensional data as well as geometric features of the measured object are provided for both on-line and off-line analysis.



Element : plane

☑ Activate Remote Control

Points
0

Probe Position [mm]
X : -29.98
Y : 110.39
Z : -69.69

Output Panel
Centroid [mm]
-58.46 110.33 -70.63
Direction cosines
-0.0019519 0.0045628 -0.99999

Zoom Panel
Centroid 0 0 0

Figure 6. A screenshot of the graphical user interface for managing the dimensional measurement task (example of a plane reconstruction task).

3.4. Experimental tests for preliminary metrological characterisation

Preliminary experimental tests have been carried out to evaluate prototype performance (in terms of measurement accuracy, repeatability and reproducibility) as well as system potentialities.

The data herein discussed refers to a network layout consisting of six wireless IR cameras, arranged in a 5.0 × 6.0 × 3.0 m working environment according to a grid-based configuration. Cameras were oriented towards the centre of the laboratory, in order to ensure better volume coverage and measurements redundancy. Figure 3 shows a virtual reconstruction of the experimental setup.

The black wireframe represents the camera 'field-of-sensing', whereas the light grey wireframe represents the working volume (interpreted as the volume of intersection of at least two 'field-of-sensing'). It has to be noted that the actual working volume was about 2.0 × 2.0 × 2.0 m in width.

A first evaluation of the measurement accuracy of point coordinates, intended as the 'closeness of agreement between a measured quantity value and a true quantity value of a measurand' (VIM 2008), has been carried out using a 3D aluminium alloy calibrated artefact (see Figure 7). To have a set of reference points with known nominal positions, 22 points on the artefact have been calibrated (at nominal temperature $T = 21^\circ\text{C}$ and relative humidity $\text{RH} = 27\%$) using a coordinate-measuring machine (DEA IOTA 0101).

Figure 7. The reference artefact used for the accuracy test.

The reference points have been measured by the MScMS-II system prototype, by moving the artefact in five different positions uniformly distributed within the working volume. Figure 8 shows the histogram of the distances between measured and nominal positions.

It is noteworthy how the 50% of the measured points is within a distance of 1.87 mm from the nominal position, while the 94.2% of results is less than 5-mm far from the nominal position (Galetto

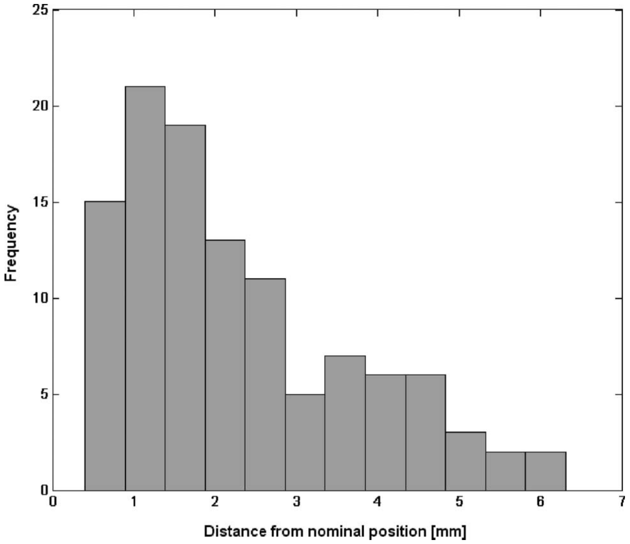


Figure 8. Accuracy in distance measurement. Histogram of the distances between measured and nominal positions.

et al. 2009). At worst, the maximum measured distance is below 6.5 mm. By considering several issues (e.g. geometric distortion of the reconstructed working volume and measurement process) whose effects on measurements strongly depend on the location within the working volume, the severe experimental testing procedure consistently affect the extent of measurement errors as well as their high variability.

In a second test, measurement repeatability of point coordinates, intended as 'closeness of the agreement between the results of successive measurements of the same measurand carried out under the same conditions of measurement' (VIM 2008), has been tested on five different points, uniformly distributed within the working volume, by repositioning the probe in the same positions for $k = 30$ times. It is noteworthy that repeatability characteristics are related to the sensor device performance as well as to the operator skills. Human skills actually represent an external factor related to capabilities in holding the probe in a fixed position. The sample standard deviation of repeatability tests was found to be smaller than 1.25 mm (Galetto *et al.* 2009).

Finally, measurement reproducibility of point coordinates, intended as 'closeness of the agreement between the results of successive measurements of the same measurand carried out under changed conditions of measurement' (VIM 2008), has been tested with reference to five points, repeating the measurement $k = 30$ times with different mobile probe orientations. Reproducibility tests stress the importance on measurement quality of network and probe relative position and orientation. A sample standard deviation smaller than 3.45 mm has been obtained (Galetto *et al.* 2009).

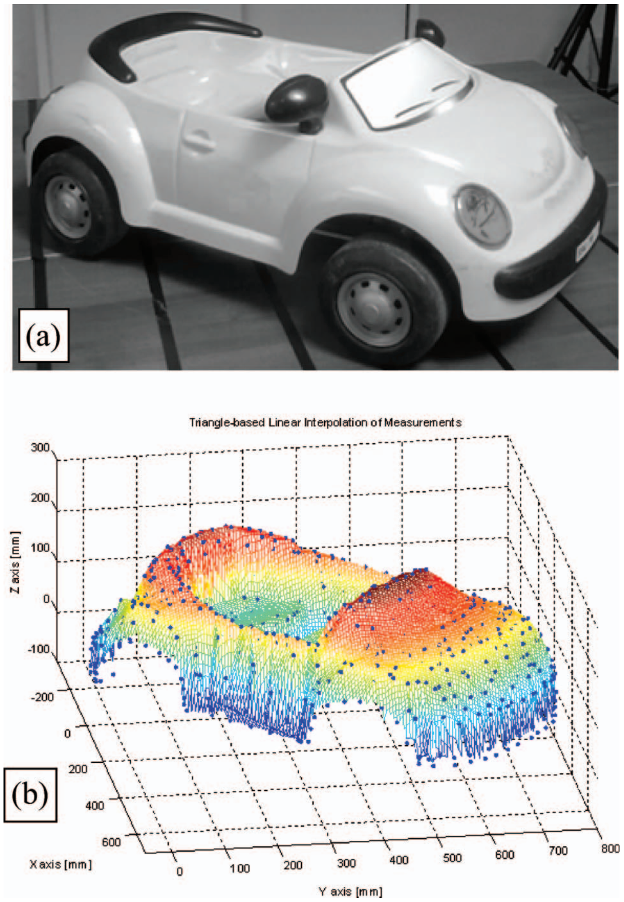


Figure 9. (a) Toy car model. (b) Measured points and reconstructed shape.

According to the results emerging from these tests, MScMS-II prototype do not appear to be very competitive if compared with commercial systems such as CMMs, laser trackers, iGPS. With those technologies, in the same working volume, accuracy deviation may range from few micrometers up to 1 mm at worst, depending on the system and the working conditions (Franceschini *et al.* 2009a, Maisano *et al.* 2009).

However, these results become particularly interesting if cost and potentiality of MScMS-II are considered. While ensuring scalability and flexibility that existing commercial systems cannot guarantee, the prototype still has significant room for enhancement mainly related to the improvement of the employed technology. Because the state-of-the-art of IR cameras actually provides a wide choice of resolution (from less than 1 megapixel up to 16 megapixels), current CCD sensors (128 × 96 pixels of native resolution) could be easily replaced with higher performance ones. Commercially available solutions generally enable intelligent features such as on-board 2D image analysis and processing, making the computational workload almost independent of the IR sensor resolution. Nonetheless, a trade-off between the target system performance and the economic impact of the entire system has to be found.

Furthermore, because of its ease-of-use and fast data acquisition characteristics, the MScMS-II can be applied also for geometry reconstruction and reverse engineering tasks by untrained operators. As an example, the chassis of a toy car model has been geometrically reconstructed through a triangle-based linear interpolation relying on 690 measured points gathered by an unskilled operator in about 1 hr (see Figure 9).

4. Conclusions

This article discusses the concept of distributed systems for large-scale dimensional metrology tasks. These systems – due to their nature – are more flexible and suitable than centralised systems. Furthermore, if they are composed by 'intelligent' sensing units, they can implement network logics (such as auto-diagnostics, compensation, correction, substitution, etc.) that can improve the overall performance of the system itself. The proposed approach, based on WSNs, demonstrates to have the potentialities of being fully distributed and combining flexibility and network logics.

A prototype implementation, based on a WSN of IR cameras, has been used to test system feasibility and demonstrated satisfactory metrological performance and appealing flexibility, and scalability properties. The prototype represents a step towards fully distributed systems, because it implements a fully distributed approach for measurement data acquisition and both centralised and distributed logics for data elaboration and sensor management.

Future research efforts will go in the direction of a self-coordination of the remote sensor devices as to diagnostics and compensation. Although accuracy resulted to be relatively good in view of the technology used, further studies are intended to increase the resolution of the optical devices, in order to enhance the accuracy and working volume coverage.

References

Akyildiz, I.F., Melodia, T., and Chowdhury, K.R., 2007. A survey on wireless multimedia sensor networks. *Computer Networks*, 51 (4), 921–960.

Akyildiz, I.F., Melodia, T., and Chowdhury, K.R., 2008. Wireless multimedia sensor networks: applications and testbeds. *Proceedings of the IEEE*, 96 (10), 1588–1605.

Akyildiz, I.F., *et al.*, 2002. Wireless sensor networks: a survey. *Computer Networks*, 38 (4), 393–422.

ARC Second, 2010. Product literature [online]. Available from: http://arcsecond.com [Accessed 24 October 2009].

Automated Precision, 2009. Automated Precision Inc. website [online]. Available from: http://www.apisensor.com/tracker3.html [Accessed 4 November 2009].

Axios 3D, 2009. Axios 3D Services GmbH website [online]. Available from: http://www.axios3d.de/ [Accessed 4 November 2009].

Bredin, J.L., *et al.*, 2005. Deploying sensor networks with guaranteed capacity and fault tolerance. *In*: *Proceedings of the 6th ACM international symposium on Mobile ad hoc networking and computing*, New York: ACM, 309–319.

Bulusu, N., Heidemann, J., and Estrin, D., 2001. Adaptive beacon placement. *Proceedings of the 21st international conference on distributed computing systems*, Los Alamitos, CA: IEEE Computer Society, 489–498.

Cassandras, C.G. and Li, W., 2005. Sensor networks and cooperative control. *European Journal of Control*, 11 (4–5), 436–463.

Cuypers, W., *et al.*, 2009. Optical measurement techniques for mobile and large-scale dimensional metrology. *Optics and Lasers in Engineering*, 47 (3–4), 292–300.

Ding, M., *et al.*, 2007. Fault-tolerant target localization in sensor networks. *EURASIP Journal on Wireless Communications and Networking*, 2007 (1), 1–9.

Doğançay, K., 2005. Bearings-only target localization using total least squares. *Signal Processing*, 85 (9), 1695–1710.

Faro Technologies, 2009. Faro Technologies Company website [online]. Available from: http://www.faro.com [Accessed 16 April 2009].

Ferri, C., Mastrogiacomo, L., and Faraway, J., 2010. Sources of variability in the set-up of an indoor GPS. *International Journal of Computer Integrated Manufacturing*, 23 (6), 487–499.

Franceschini, F., Mastrogiacomo, L., and Pralio, B., 2009d. An unmanned aerial vehicle-based system for large scale metrology applications. *International Journal of Production Research*, 48 (13), 3867–3888.

Franceschini, F., *et al.*, 2009a. Mobile spatial coordinate measuring system (MScMS) – introduction to the system. *International Journal of Production Research*, 47 (14), 3867–3889.

Franceschini, F., *et al.*, 2009b. On-line diagnostics in the mobile spatial coordinate measuring system (MScMS). *Precision Engineering*, 33, 408–417.

Franceschini, F., *et al.*, 2009c. A review of localization algorithms for distributed wireless sensor networks in manufacturing. *International Journal of Computer Integrated Manufacturing*, 22 (7), 698–716.

Franceschini, F., *et al.*, 2008. The problem of distributed wireless sensors positioning in the mobile spatial coordinate measuring system (MScMS). *In*: *Nineth biennial ASME conference on engineering systems design and analysis ESDA08,* 7–9 July 2008 Haifa, Israel. New York: ASME, 317–327.

Galetto, M. and Pralio, B., 2010. Optimal sensor positioning for large scale metrology applications. *Precision Engineering*, 34 (3), 563–577.

Galetto, M., Mastrogiacomo, L., and Pralio, B., 2009. An innovative indoor coordinate measuring system for large-scale metrology based on a distributed IR sensor network. *In*: *Proceedings of ASME 2009 international manufacturing science and engineering conference MSEC2009,* October 2009, IN, USA, New York: ASME, CD-Rom.

Ganci, G. and Handley, H., 1998. Automation in videogrammetry. *International Archives of Photogrammetry and Remote Sensing*, 32 (5), 53–58.

Geodetic Services, 2010. Geodetic Services Inc. website [online]. Available from: http://www.geodetic.com [Accessed 8 February 2010].

Han, X., *et al.*, 2007. Fault-tolerant relay nodes placement in heterogeneous wireless sensor networks. *In*: *Proceedings of the 26th IEEE/ACM joint conference on computers and communications (INFOCOM'07)*, 6–12 May, Anchorage, AK, Piscataway, NJ: IEEE, 1667–1675.

Hao, B., Tang, H., and Xue, G., 2004. Fault-tolerant relay node placement in wireless sensor networks: formulation and approximation. *In*: *Proceedings of the Workshop on High Performance Switching and Routing (HPSR'04)*, 19–21 April Phoenix, AZ, Piscataway, NJ: IEEE, 246–250.

Hartley, R.I. and Zisserman, A., 2004. *Multiple view geometry in computer vision*. Cambridge: Cambridge University Press.

Hofmann-Wellenhof, B., Lichtenegger, H., and Collins, J., 1997. *GPS: theory and practice*. Wien: Springer-Verlag.

Koushanfar, F., Potkonjak, M., and Sangiovanni-Vincentelli, A., 2004. Fault tolerance in wireless sensor networks. *in Handbook of Sensor Networks*. Boca Paton, FL: CRC Press, 812–829.

Kwakkernaat, M.R.J.A.E., *et al.*, 2008. High-resolution angle-of-arrival measurements on physically-nonstationary mobile radio channels. *IEEE Transactions on Antennas and Propagation*, 56 (8), 2720–2729.

Leica Geosystems, 2009. Leica Geosystems Company website [online]. Available from: http://www.leica-geosystems.com [Accessed 4 November 2009].

Laguna, M., *et al.*, 2009. Diversified local search for the optimal layout of beaconsin an indoor positioning system. *IIE Transactions*, 41, 247–259.

Maisano, D., *et al.*, 2009. Comparison of two distributed large volume measurement systems: MScMS and iGPS. *Proceedings of the Institution of Mechanical Engineers. Part B: Journal of Engineering Manufacture*, 223 (5), 511–521.

Mason, S., *et al.*, 1997. Heuristic reasoning strategy for automated sensor placement. *Photogrammetric Engineering and Remote Sensing*, 63, 1093–1102.

Mastrogiacomo, L. and Maisano, D., 2010. Network localization procedures for experimental evaluation of mobile spatial coordinate measuring system (MScMS). *The International Journal of Advanced Manufacturing Technology*, 48 (9), 859–870.

Metronor, 2009. Metronor Corporate website [online]. Available from: http://www.metronor.com [Accessed 10 June 2009].

Mikhail, E.M., Bethel, J.S., and McGlone, J.C., 2001. *Introduction to modern photogrammetry*. New York, NY: Wiley.

Munkelt, C., *et al.*, 2009. View planning for 3D reconstruction using time-of-flight camera data. *DAGM 2009*, LNCS 5748, 352–361.

Nikon Metrology, 2010. Nikon Metrology website [online]. Available from: http://www.nikonmetrology.com [Accessed 26 February 2010].

Northern Digital, 2009. Northern Digital Inc. website [online]. Available from: http://www.ndigital.com/industrial/products-pcmm.php [Accessed 4 November 2009].

Olague, G. and Mohr, R., 2002. Optimal camera placement for accurate reconstruction. *Pattern Recognition*, 35, 927–944.

Optitrack, 2009. NaturalPoint Company website [online]. Available from: http://www.naturalpoint.com/optitrack [Accessed 3 December 2009].

Peggs, G.N., *et al.*, 2009. Recent developments in large-scale dimensional metrology. *Proceedings of the Institution of Mechanical Engineers, Part B, Journal of Engineering Manufacture*, 223 (6), 571–595.

Puttock, M.J., 1978. Large-scale metrology. *Annals of CIRP*, 21 (1), 351–356.

Ray, P.K. and Mahajan, A., 2002. A genetic algorithm-based approach to calculate the optimal configuration of ultrasonic sensors in a 3D position estimation system. *Robotics and Autonomous Systems*, 41, 161–177.

Svoboda, T., Martinec, D., and Pajdla, T., 2005. A convenient multi-camera self-calibration for virtual environments. *PRESENCE: Teleoperators and Virtual Environments*, 14 (4), 407–422.

3rdTech, 2010. 3rdTech Inc. website [online]. Available from: http://www.3rdtech.com [Accessed 2 February 2010].

Vicon, 2009. Vicon Inc. website [online]. Available from: http://www.vicon.com [Accessed 3 December 2009].

VIM, 2008. *International vocabulary of basic and general terms in metrology*. Geneva, Switzerland: International Organization for Standardization.

Wang, Z., *et al.*, 2008. Experimental deployment of the indoor GPS large volume metrology system in a large scale production facility. *In*: *Proceedings of the third international conference on manufacturing engineering (ICMEN),* 1–3 October 2008 Chalkidiki, Greece, 827–836.

Weckenmann, A., Hartmann, W., and Weickmann, J., 2008. Model and simulation of fringe projection measurements as part of an assistance system for multi-component fringe projection sensors. *Proceedings of SPIE*, 7102, 71020N-1–71020N12.

Welch, G., *et al.*, 2001. High-performance wide-area optical tracking the HiBall tracking system. *Presence: Teleoperators and Virtual Environments*, 10 (1), 1–21.

Younis, M. and Akkaya, K., 2008. Strategies and techniques for node placement in wireless sensor networks: a survey. *Ad Hoc Networks*, 6, 621–655.