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Statistics for Innovation

Statistical Design of "Continuous" Product Innovation

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Chapter 9
An Innovative Online Diagnostic Tool for a Distributed Spatial Coordinate Measuring System

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Abstract There is currently an increasing trend for accurate measurements of large-scale lengths; in particular, 3D coordinate metrology at length scales of 5 m to 60 m has become a routine requirement in industries such as aircraft and ship construction. This chapter focuses on the Mobile Spatial coordinate Measuring System (MScMS), a new system developed at the Industrial Metrology and Quality Engineering Laboratory of DISPEA of the Politecnico di Torino. Based on a distributed sensor network structure, MScMS is designed to perform simple and rapid indoor dimensional measurements of large-size objects. Using radiofrequency (RF) and ultrasound (US) signals, the system makes it possible to localize—in terms of spatial coordinates—the points "touched" by a wireless mobile probe. To protect the system from potential causes of error, such as US signal diffraction and reflection, external uncontrolled US sources (key jingling, neon blinking, etc.) or unacceptable software solutions, MScMS implements some statistical tests in order to perform online diagnostics. One of these tests is analyzed in depth in this chapter: the "energy model-based diagnostics test." Although it is specifically developed for the MScMS

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system, this test can easily be extended to other recent large-scale metrology systems based on distributed devices—such as the Metris indoor-GPS, the Metronor Portable CMM, and the 3rd Tech Hi-Ball.

9.1 Introduction

In many industrial fields (automotive, aerospace, etc.), it is necessary to quickly and easily take dimensional measurements of large-size objects (Bosch 1995; Cauchick-Miguel et al. 1996; Hansen and De Chiffre 1999; Franceschini et al. 2007; Franceschini and Galetto 2007). At present, this problem can be handled using various metrological systems based on different technologies (optical, mechanical, electromagnetic, etc.). These systems are more or less adequate, depending on the measuring conditions, the user's experience and skill, the cost, accuracy, portability, etc. When measuring medium-to-large-size objects, portable systems are generally preferred to fixed ones. Transferring the measuring system to the location of the object to be measured is often more practical than moving the object to the measuring system (Bosch 1995).

The performances of most measuring systems, independent of their technology and features, can be affected by several sources of error, such as temperature, humidity, light, vibrations, etc. For this reason, the use of diagnostic tools to control measuring activities and to assist in the detection of abnormal functioning can be very helpful.

This chapter analyzes some online diagnostic tools implemented in the Mobile Spatial coordinate Measuring System (MScMS) that can be used to continuously monitor the reliability of its measurements.

MScMS, which was developed at the Industrial Metrology and Quality Engineering Laboratory of DISPEA of the Politecnico di Torino, is based on a distributed sensor network structure (Franceschini et al. 2008b). The system is designed to perform dimensional measurements of medium-to-large-size objects (longerons of railway vehicles, airplane wings, fuselages, etc.). These objects are difficult to measure using traditional coordinate measurement systems such as coordinate measurement machines (CMMs) because of their limited working volumes (ISO 10360, part 2 2001; Bosch 1995). The working principle of MScMS is very similar to that adopted by the well-known NAVSTAR GPS (NAVigation Satellite Timing And Ranging Global Positioning System) (Hofmann-Wellenhof et al. 2001). The main difference is that MScMS is based on US technology aimed at evaluating spatial distances instead of RF. MScMS is easily adaptable to different measuring environments and does not require complex procedures for installation, start-up or calibration (Franceschini et al. 2008b).

Although the diagnostic tools presented in this chapter are specifically developed for the MScMS system, they can be easily extended to other recent large-scale metrology systems consisting of distributed devices, such as the Metris indoor-GPS, the Metronor Portable CMM and the 3rd Tech Hi-Ball (Metris 2008; Metronor 2008; Welch et al. 2001).

9.2 The Concept of the "Reliability of a Measurement"

When we refer to the field of CMMs, the concept of "online metrological performance verification" is strictly related to the notion of "online self-diagnostics" (Gertler 1998; Franceschini and Galetto 2007). In some senses, this approach is complementary to that of uncertainty evaluation (ISO/TS 15530–6 2000; Phillips et al. 2001; Savio et al. 2002; Piratelli-Filho and Di Giacomo 2003; Feng et al. 2007). In general, an online measurement verification is a guarantee of the preservation of a measurement system's characteristics (including accuracy, repeatability and reproducibility) (VIM 2004; GUM 2004). The effect of measuring system degradation is the production of unreliable measurements.

In general, we can define the concept of the "reliability of a measurement" as follows.

For each measurable value x, we can define an acceptance interval $[\mathrm{LAL}, \mathrm{UAL}]$ (where LAL stands for lower acceptance limit and UAL for upper acceptance limit): $\mathrm{LAL} \leq x \leq \mathrm{UAL}$.

The measure y of the quantity x, obtained by a given measurement system, may be considered the realization of a random variable Y. It is considered "reliable" if $\mathrm{LAL} \leq y \leq \mathrm{UAL}$.

Therefore, the I and II type probability errors (misclassification rates) correspond, respectively, to:

$$\alpha = \Pr\{Y \notin [\mathrm{LAL}, \mathrm{UAL}]\,|\mathrm{LAL} \leq x \leq \mathrm{UAL}\} \tag{9.1}$$

and

$$\beta = \Pr\{\mathrm{LAL} \leq y \leq \mathrm{UAL}\,|x \notin [\mathrm{LAL}, \mathrm{UAL}]\} \tag{9.2}$$

from the point of view of the measurement system.

LAL and UAL are not usually known a priori.

The acceptance interval is defined by considering the metrological characteristics of the measurement system (accuracy, reproducibility, repeatability, etc.), as well as the required quality level of the measurement result (VIM 2004; GUM 2004).

The problem of online system self-diagnostics is not a recent matter, and many strategies have been proposed in different fields to address it (Clarke 1995; Henry and Clarke 1992; Isermann 1984). In the most critical sectors, such as the aeronautical and nuclear ones, where there is an absolute need to promptly detect every malfunction, the typical approach is based on "physical redundancy". This principally consists of instrumentation and system control device replication. Although effective, this method can affect system cost and complexity (Gertler 1998).

An alternative and/or complementary method to physical redundancy is "model-based redundancy" (also called "analytical redundancy"). This approach replaces the replication of physical instrumentation with the use of appropriate mathematical models. Such models may be derived from applying physical laws to experimental data or from self-learning methods (for example, neural networks). These kinds of diagnostics allow the detection of system failures by comparing measured and model-elaborated process variables (Gertler 1998; Reznik and Solopchenko 1985; Franceschini and Galetto 2007).

The basic idea behind the self-diagnostic method described in this chapter is to define an acceptance interval. If the measurement value (y) is included in this interval, the acceptance test gives a positive response and the measured result is considered reliable. Otherwise, the measurement is rejected (Franceschini et al. 2008a).

After a general description of MScMS, the chapter focuses on the online diagnostic tool. A numerical example is presented and discussed. The following aspects are analyzed in detail: a theoretical description of the test; empirical definitions of the test parameters and acceptance limits; trial runs and preliminary experimental results; critical aspects and possible improvements.

9.3 MScMS Technological and Operating Features

The MScMS prototype is made up of three main components (see Fig. 9.1) (Franceschini et al. 2008b):

- A constellation (network) of wireless devices ("Crickets"), which are opportunely distributed around the working area
- A measuring probe that communicates via ultrasound transceivers (US) with constellation devices in order to obtain the coordinates of the touched points
- A computing and control system (PC), which receives and processes data sent by the mobile probe in order to evaluate the geometrical features of objects

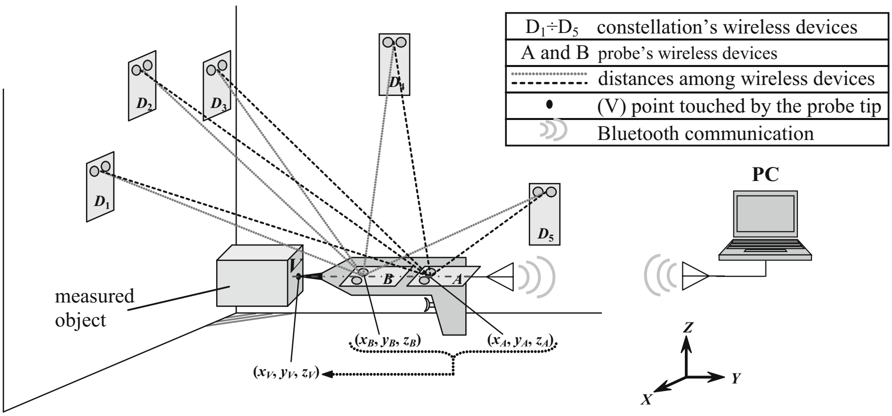

Fig. 9.1 MScMS working scheme

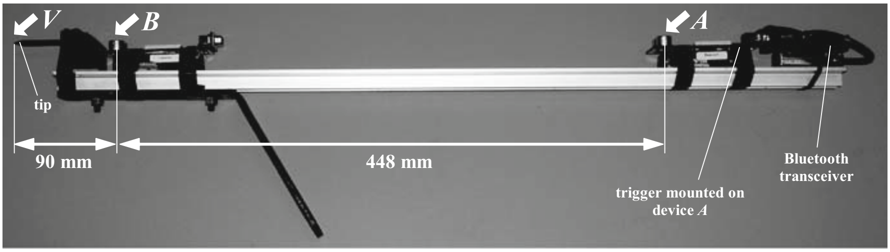

Fig. 9.2 Mobile probe prototype. The distance between the two probe devices is a construction parameter defined during the probe design phase

The measuring probe comprises a mobile system that hosts two wireless devices, a tip to touch the surface points of the measured objects, and a trigger to activate data acquisition (see Fig. 9.2) (Franceschini et al. 2008b).

Given the geometrical characteristics of the mobile probe, the tip coordinates can be univocally determined by means of the spatial coordinates of the two probe Crickets (Franceschini et al. 2008b).

The Crickets are being developed by the Massachusetts Institute of Technology and Crossbow Technology Inc. They utilize one radiofrequency (RF) and two ultrasound (US) transceivers in order to communicate and evaluate mutual distances (see Fig. 9.3) (MIT CSAIL 2004). Mutual distances are estimated by a technique known as TDoA (time difference of arrival) (Gustafsson and Gunnarsson 2003). RF communication allows each Cricket to rapidly find out distances between the devices. A Bluetooth transmitter connected to one of the two probe Crickets sends this distance information to the PC, which is equipped with ad hoc software that can analyze it.

The system makes it possible to calculate the location—in terms of spatial coordinates—of the object points that are "touched" by the probe. More precisely,

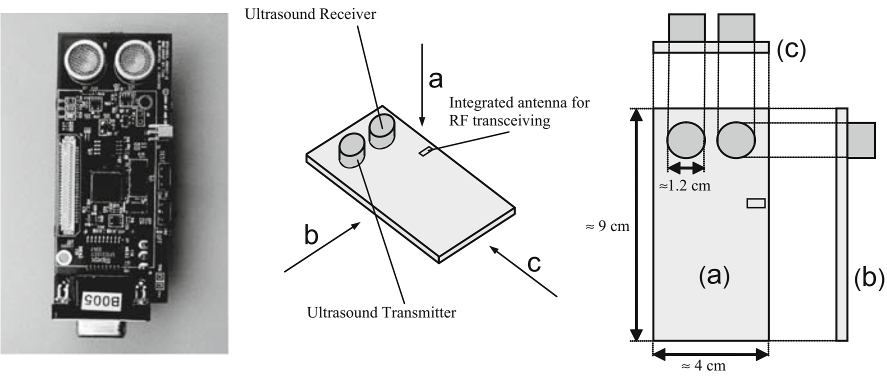

Fig. 9.3 Cricket structure (MIT CSAIL 2004); reproduced here with permission

when the trigger mounted on the mobile probe is pulled, the current distances between the probe Crickets and the constellation ones are sent to the PC. These data are utilized to calculate the touched point coordinates. In this way, different types of calculations can be performed, such as determinations of distances, geometrical tolerances, geometrical curves or object surfaces (Franceschini et al. 2008b).

The constellation devices (Crickets) operate as reference points (beacons) for the mobile probe. The spatial location and the calibration of the constellation devices are achieved by a specific procedure that utilizes a "trilateration" technique (Lee and Ferreira 2002a, 2002b; Franceschini et al. 2008b).

To uniquely determine the location of a point in 3D space, at least four reference points are generally needed (Chen et al. 2003; Sandwith and Predmore 2001; Akcan et al. 2006). In general, a trilateration problem can be formulated as follows. Given a set of N nodes with known coordinates (x_i, y_i, z_i), $i = 1, \ldots, N$, and a set of measured distances d_{M_i} from a given point $P \equiv (x_P, y_P, z_P)$, the following system of nonlinear equations needs to be solved to compute the unknown coordinates (x_P, y_P, z_P) of P (see Fig. 9.4):

$$\begin{bmatrix} (x_1 - x_P)^2 + (y_1 - y_P)^2 + (z_1 - z_P)^2 \\ (x_2 - x_P)^2 + (y_2 - y_P)^2 + (z_2 - z_P)^2 \\ \vdots \\ (x_N - x_P)^2 + (y_N - y_P)^2 + (z_N - z_P)^2 \end{bmatrix} = \begin{bmatrix} d_{M_1}^2 \\ d_{M_2}^2 \\ \vdots \\ d_{M_N}^2 \end{bmatrix} \tag{9.3}$$

If this trilateration problem is over-defined (i.e., four or more reference points are available), it can be solved using a least mean squares approach (Savvides et al. 2001).

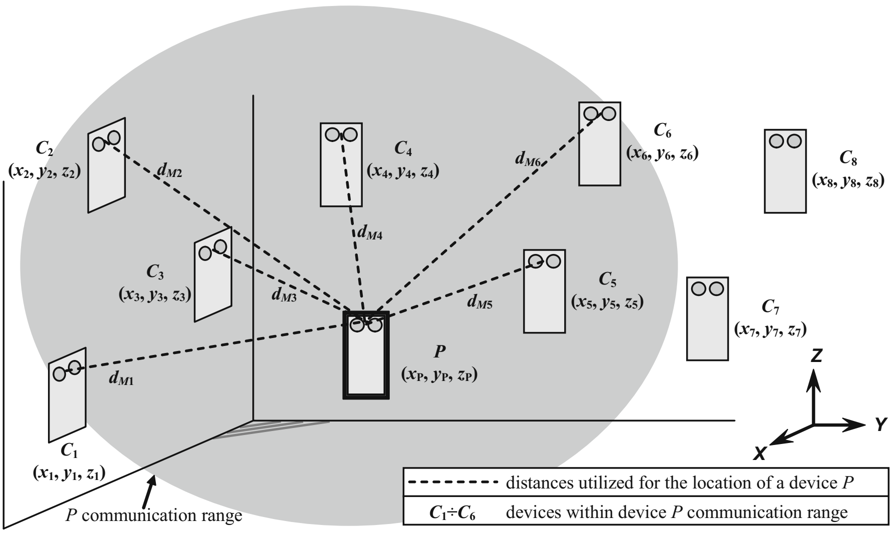

Fig. 9.4 Location of a generic device *P*

The location of each unknown node can be estimated by performing iterative minimization of the following error function ($\mathrm{EF}(\mathbf{x}_P)$) (Franceschini et al. 2008b):

$$\mathrm{EF}(\mathbf{x}_P) \equiv \frac{\sum_{i=1}^{N}(d_{C_i} - d_{M_i})^2}{N} \tag{9.4}$$

where:

- N is the number of reference points $\mathbf{x}_i = (x_i, y_i, z_i)$, $i = 1, \ldots, N$ known a priori
- $\mathbf{x}_P = (x_P, y_P, z_P)$ are the unknown coordinates of the point P in the localization space $\xi \subseteq \mathbb{R}^3$
- d_{M_i} is the measured distance between the i-th reference point and P
- d_{C_i} is the Euclidean distance between the i-th reference point and P:

$$d_{C_i} = \sqrt{(x_P - x_i)^2 + (y_P - y_i)^2 + (z_P - z_i)^2}\,. \tag{9.5}$$

The problem of finding the minimum of the function $\mathrm{EF}(\mathbf{x}_P)$ can be treated as the problem of finding the point of equilibrium for a mass–spring system (lowest potential energy) (Moore et al. 2004; Franceschini et al. 2008a).

As an example, let us consider the 2D situation described in Fig. 9.5. A unitary mass is associated with each network node. The node with an unknown location is connected to three reference nodes by three springs. Each of these has a rest length equal to the measured distance and a unitary force constant.

Knowing the rest lengths (d_{M_i}) and the locations of the masses, the system potential energy is given by:

$$U(\mathbf{x}_P) = \sum_{i=1}^{N} \frac{1}{2}\left(\sqrt{(x_P - x_i)^2 + (y_P - y_i)^2} - d_{M_i}\right)^2\,. \tag{9.6}$$

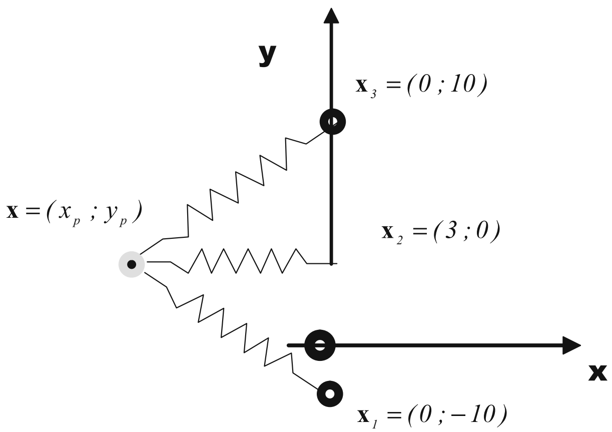

Fig. 9.5 An example of 2D mass–spring system. Three reference nodes ($\mathbf{x}_1, \mathbf{x}_2, \mathbf{x}_3$) with known locations are linked by springs to the point to be localized ($\mathbf{x}_P$)

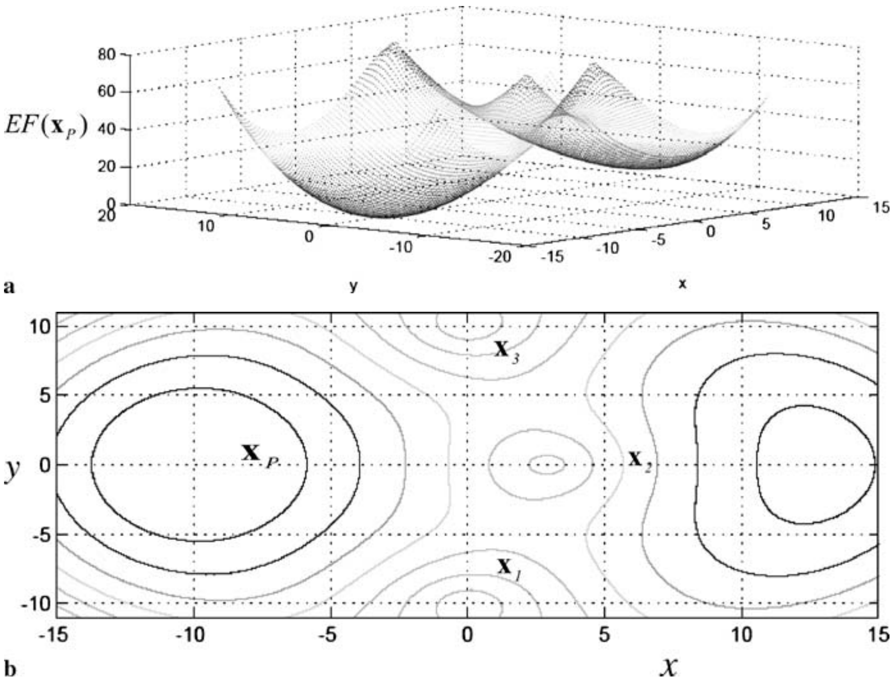

Fig. 9.6 **a** $EF(\mathbf{x}_P)$ behavior for the mass–spring system described in Fig. 9.5. Finding the minimum point means localizing the node P that has an unknown location. **b** Isoenergetic curves for the mass–spring system described in Fig. 9.5. Note that $\mathbf{x}_P$ is the global minimum point of potential energy. The maxima correspond to the reference points $(\mathbf{x}_1, \mathbf{x}_2, \mathbf{x}_3)$. *Black curves* refer to low energy levels, *gray curves* refer to high energy levels

Figure 9.6 shows 3D and 2D visualizations of $EF(\mathbf{x}_P)$. Since $EF(\mathbf{x}_P) \propto U(\mathbf{x}_P)$, they have the same minima. As expected, the global minimum represents the position of the node that we wish to locate ($P \equiv (-10;0)$).

9.4 MScMS Diagnostic System

Since it is based upon US technology, MScMS is sensitive to many influential factors. US signals may be diffracted and reflected by obstacles interposed between two devices, uncontrolled external events can become undesirable US wave sources, or positioning algorithms can produce unacceptable solutions. These and other potential causes of accidental measurement errors must be checked for to ensure proper levels of accuracy.

In order to protect the system, MScMS implements a series of statistical tests for online diagnostics. The one analyzed in this chapter is the "energy model-based diagnostics test."

9.5 Energy Model-Based Diagnostics

$\mathrm{EF}(\mathbf{x}_P)$ is non-negative by definition (see Eq. 9.6). In particular, $\mathrm{EF}(\mathbf{x}_P) = 0$ when $d_{M_i} = d_{C_i}$, for $i = 1,\ldots,N$. Because of the natural variability of the measuring instrument, two typical situations may occur:

- $\mathrm{EF}(\mathbf{x}_P)$ is strictly positive, even at the correct point of localization.
- $\mathrm{EF}(\mathbf{x}_P)$ shows a global minimum at a point that is not the correct one. In other words, due to the "noise" in distance measurements, a local minimum may turn into a global minimum and vice versa.

Energy model-based diagnostics introduces a criterion in order to identify all unacceptable minima solutions for $\mathrm{EF}(\mathbf{x}_P)$ and thus prevent system failures. Such a criterion enables the MScMS system to distinguish between reliable and unreliable measurements.

Consider a solution $\mathbf{x}_P^*$ to the problem $\min_{\mathbf{x}_P \in \xi} \mathrm{EF}(\mathbf{x}_P)$. In general, if the problem is overdetermined (i.e., there are more than three distance constraints in the 3D case and more than two in the 2D case) and the individual measurements are affected by noise, the solution that satisfies all distance constraints at the same time does not exactly fit the real location of the node (see Fig. 9.7).

In such a case, the differences between measured and Euclidean distances may be defined as residuals ($\varepsilon_i \equiv (d_{M_i} - d_{C_i})$). Generally, in the absence of systematic sources of error, it is reasonable to hypothesize a normal distribution for the random variables ε_i, i.e.:

$$\varepsilon_i \equiv (d_{M_i} - d_{C_i}) \sim N\left(0, \sigma_i^2\right) \ . \tag{9.7}$$

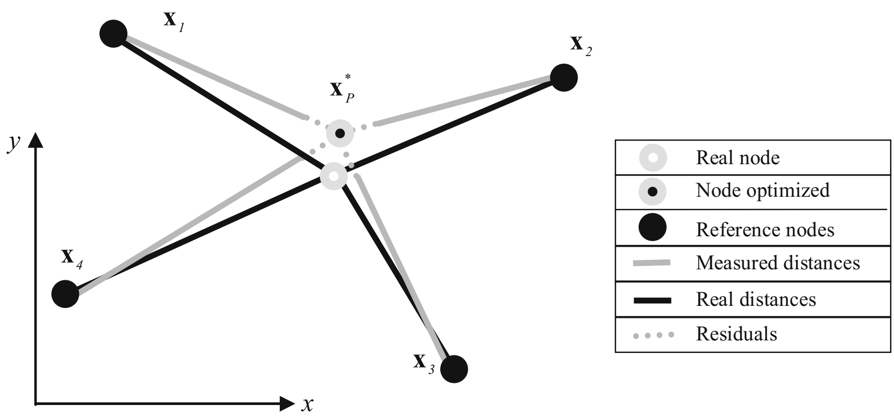

Fig. 9.7 An example of possible node localization. Measured distances are not equal to real distances

If $\sigma_i^2 = \sigma^2$, $\forall i$ (this is true in the absence of spatial/directional effects), Eq. 9.4 becomes:

$$\mathrm{EF}(\mathbf{x}_P) = \sum_{i=1}^{N} \frac{(d_{M_i} - d_{C_i})^2}{N} = \sum_{i=1}^{N} \frac{\varepsilon_i^2}{N} = \frac{\sigma^2}{N} \cdot \sum_{i=1}^{N} \frac{\varepsilon_i^2}{\sigma^2} = \frac{\sigma^2}{N} \cdot \sum_{i=1}^{N} \left(\frac{\varepsilon_i}{\sigma}\right)^2 = \frac{\sigma^2}{N} \cdot \sum_{i=1}^{N} z_i^2 . \tag{9.8}$$

Equation 9.8 can be seen as the sum of N independent normal squared random variables with zero mean and unit variance, multiplied by the constant term $\frac{\sigma^2}{N}$.

It should be noted that the sum in Eq. 9.8 has only $N-1$ independent terms. Equation 9.8 causes the loss of a degree of freedom. This implies that, once $N-1$ terms are known, the N-th one is univocally determined.

When χ_P^2 is defined as $\chi_P^2 = \sum_{i=1}^{N} (\frac{\varepsilon_i}{\sigma})^2$, $\mathrm{EF}(\mathbf{x}_P)$ in Eq. 9.8 has a chi-square distribution with $N-1$ degrees of freedom:

$$\mathrm{EF}(\mathbf{x}_P) = \frac{\sigma^2}{N} \cdot \chi_P^2 . \tag{9.9}$$

The residual variance σ^2 can be estimated a priori for the whole measuring space, for example during the phase of installation and calibration of the system.

Every time a measurement is performed for each probe Cricket, the MScMS diagnostic software computes the following quantity (experimental chi-square):

$$\chi_P^{2*} = \mathrm{EF}(\mathbf{x}_P^*) \frac{N}{\sigma^2} . \tag{9.10}$$

Assuming that the risk α is a type I error, a one-sided confidence interval for variable $\chi^2_{\nu,\alpha}$ can be calculated. $\chi^2_{\nu,\alpha}$ is a chi-square distribution with $\nu = N-1$ degrees of freedom and a confidence level of $1-\alpha$. The confidence interval is assumed to be the acceptance interval for the test of the reliability of the measurement.

The test arrives at the following two alternative conclusions:

- $\chi_P^{2*} \leq \chi^2_{\nu,\alpha} \rightarrow$ the measurement is not considered unreliable; hence it is not rejected
- $\chi_P^{2*} > \chi^2_{\nu,\alpha} \rightarrow$ the measurement is considered unreliable; hence it is rejected and the operator is asked to perform another one

It is important to note that this test can be applied in many other different contexts in which trilateration or triangulation are utilized for coordinate measurement (3rd Tech Hi-Ball, Leica T-Probe, Metris Laser Radar and i-GPS, etc.) (Welch et al. 2001; Rooks 2004).

9.5.1 Setting Up the Test Parameters

The risk α is defined by the user according to the required level of performance of the system. A high value of α prevents unacceptable solutions to the optimization problem, minimizing the type II error β.

On the other hand, while a low value of α speeds up the measurement procedure, it may result in inaccurate data being collected due to the high level of II type error β.

The estimation of the residual variance can be evaluated in two ways: by applying the uncertainty composition law to the calculation of the coordinates, starting from the measurement uncertainty of the distances between the constellation beacons and the probe crickets (GUM 2004), or empirically, on the basis of experimental distance measurements. In this case, it is estimated from a sample of residuals obtained by measuring a set of points that are randomly distributed across the whole working volume. This method requires knowledge of the locations of the measured points a priori. It can be easily implemented during the initial phase of setting up and calibrating the system.

In the following, we focus on this second estimation procedure.

Given a set of M points distributed in the measurement space $\xi \subseteq \mathrm{I\!R}^3$, randomly measured by a single Cricket (i.e., with a random sequence of measurements and a random position and orientation of the Cricket), a set of N_j residuals can be calculated for each point j, $j = 1, \ldots, M$.

It should be noted that the number of residuals N_j may change due to the different number of distances detected during each measurement.

In the absence of systematic sources of error and time or spatial/directional effects, it is reasonable to hypothesize the same normal distribution for all the random variables ε_{ij}, $j = 1, \ldots, M$, $i = 1, \ldots, N_j$, i.e.:

$$\varepsilon_{ij} \equiv (d_{M_i} - d_{C_i})_j \sim N(0, \sigma^2)\ . \tag{9.11}$$

The variance σ^2 may be estimated as follows:

$$\hat{\sigma}^2 = \sum_{j=1}^{M} \sum_{i=1}^{N_j} \frac{(\varepsilon_{ij} - 0)^2}{\sum_{j=1}^{M} N_j} = \sum_{j=1}^{M} \sum_{i=1}^{N_j} \frac{(\varepsilon_{ij})^2}{\sum_{j=1}^{M} N_j}\ . \tag{9.12}$$

The value obtained for $\hat{\sigma}^2$ is considered the reference value for the test.

With this notation, Eq. 9.10 becomes:

$$\chi_P^{2*} = \mathrm{EF}(\mathbf{x}_P^*) \cdot \frac{N}{\sigma^2} \cong \mathrm{EF}(\mathbf{x}_P^*) \cdot \frac{N}{\hat{\sigma}^2}\ . \tag{9.13}$$

9.5.2 An Example of the Application of Energy Model-Based Diagnostics

A preliminary empirical investigation was carried out to verify the accuracy of this approach.

Considering that ultrasound sensors are able to achieve uncertainties of about 10 mm for distance measurements (confidence level $1-\alpha = 0.95$, i.e., a covering factor $k \cong 2$, according to GUM 2004) in a network consisting of five reference points (constellation beacons) placed in the measurement volume schematized in Fig. 9.8, $\hat{\sigma}^2$ was empirically estimated as follows:

- $M = 253$ points randomly distributed in the working volume were measured by a single Cricket.
- The coordinates $\mathbf{x}_j$, $j = 1,\ldots,M$, of each node were evaluated using the "mass–spring" localization algorithm and a sample of 1123 residuals were obtained.
- A normal residual distribution was tested using a chi-square test (Montgomery 2005).
- The residual variance was estimated by Eq. 9.12. The value obtained was $\hat{\sigma}^2 = 100.0\,\text{mm}^2$ (see Table 9.1 for a summary of the data).

The acceptance limit for $\text{EF}(\mathbf{x}_P)$, assuming a type I risk $\alpha = 0.05$ and $\nu = N-1 = 5-1 = 4$ degrees of freedom, is:

$$\text{EF}(\mathbf{x}_P^*) \leq \frac{\hat{\sigma}^2}{N} \cdot \chi^2_{\nu=4,\alpha=0.05} \Rightarrow \text{EF}(\mathbf{x}_P^*) \leq 189\,\text{mm}^2 \tag{9.14}$$

Consider now a typical situation that can occur when the ultrasound technology is used to estimate distances: US reflection. Referring to the configuration in Fig. 9.9, suppose that a generic point P inside the measurement volume (for example, $P \equiv (1067.2; -122.5; 925.8)$) has to be localized.

Table 9.1 Details of data analysis for estimating the standard deviation of the residuals

Sample size: $N_{\text{TOT}} = \sum_{j=1}^{M} N_j$	1123
Estimate for the mean: $\hat{\mu} = \sum_{j=1}^{M}\sum_{i=1}^{N_j} \frac{\varepsilon_{ij}}{\sum_{j=1}^{M} N_j}$	0.3 mm
Estimate for the variance: $\hat{\sigma}^2 = \sum_{j=1}^{M}\sum_{i=1}^{N_j} \frac{(\varepsilon_{ij})^2}{\sum_{j=1}^{M} N_j}$	100.0 mm^2
Maximum: $\varepsilon_{\text{MAX}} = \max\left\{\varepsilon_{ij} \mid i = 1,\ldots,N_j, j = 1,\ldots,M\right\}$	42.7 mm
Minimum: $\varepsilon_{\text{MIN}} = \min\left\{\varepsilon_{ij} \mid i = 1,\ldots,N_j, j = 1,\ldots,M\right\}$	–37.1 mm

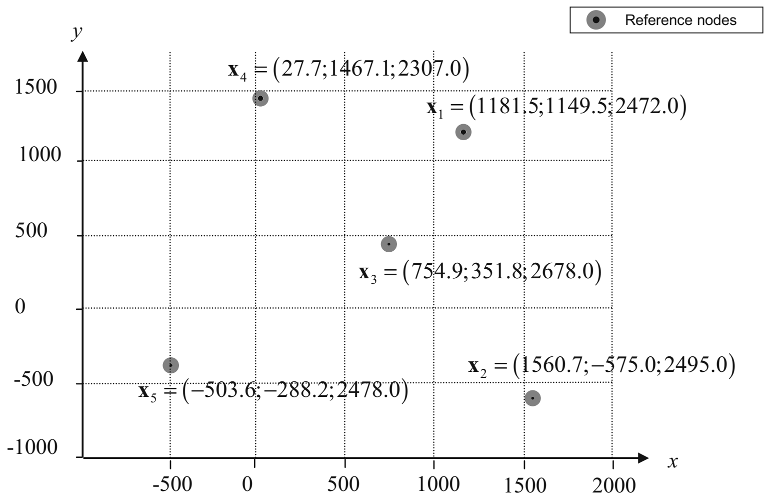

Fig. 9.8 Scheme showing the positions of the reference nodes (constellation beacons) in the measurement volume (point coordinates in millimeters [mm])

A Cricket positioned in P is able to correctly measure distances from all of the reference nodes except for one of them. An obstacle (for example, the operator performing the measurement) is interposed between P and that node, preventing direct US signal propagation. At the same time, a wall placed close to the two nodes causes US signal reflection. The consequence is that the estimate for the pairwise distance between those two nodes is 100 mm larger.

The measured distances are:

$$\begin{aligned} d_{M_1} &= 2104.8\,\text{mm} \\ d_{M_2} &= 1713.4\,\text{mm} \\ d_{M_3} &= 1831.4\,\text{mm} \\ d_{M_4} &= 2355.6\,\text{mm} \\ d_{M_5} &= 2215.2\,\text{mm} \end{aligned} \tag{9.15}$$

In this case, the algorithm produces the following wrong localization solution (see Fig. 9.10): $\mathbf{x}^*_{P'} \equiv (1022.6; -187.3; 911.8)$, characterized by a high level of "energy:" $\text{EF}(\mathbf{x}^*_P) \cong 904\,\text{mm}^2 > 189\,\text{mm}^2$.

Because of this result, the energy model-based diagnostics indicate that the measurement should be rejected.

Upon removing the obstacle, the distance from beacon 1 becomes $d_{M_1} = 2004.8\,\text{mm}$, and we obtain the correct localization solution:

$$\mathbf{x}^*_P \equiv (1067.2; -122.5; 925.8)\ . \tag{9.16}$$

The new "energy" value is: $\text{EF}(\mathbf{x}^*_P) \cong 41\,\text{mm}^2 < 189\,\text{mm}^2$, so $\mathbf{x}^*_P$ cannot be considered unreliable and the measurement is not rejected.

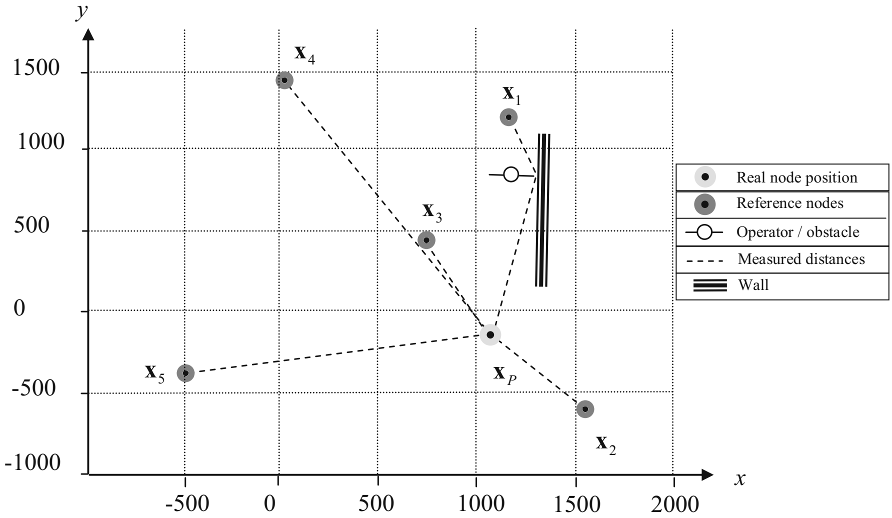

Fig. 9.9 Scheme illustrating a potentially misleading situation: walls and obstacles can result in wrong distance estimates (point coordinates are given in millimetres [mm]; see Fig. 9.8). In this case, the measured distance between node 1 and node *P* is higher than the actual distance

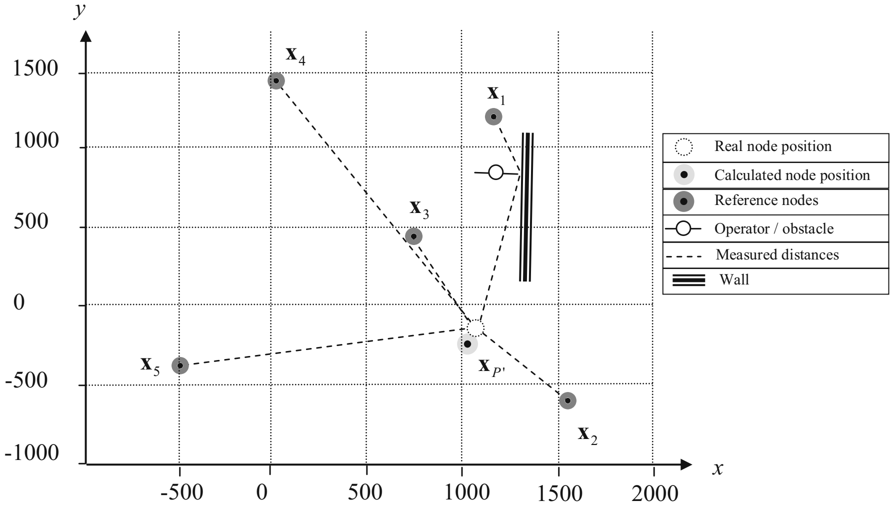

Fig. 9.10 Scheme illustrating a wrong localization solution (P') due to a wrong estimate for the distance between node 1 and node *P* (point coordinates are given in millimetres [mm]; see Fig. 9.8)

9.6 Conclusions

MScMS is an innovative wireless measuring system that is complementary to CMMs. A prototype of this system has been developed at the Industrial Metrology and Quality Engineering Laboratory of DISPEA of the Politecnico di Torino. It is portable, not very expensive, and suitable for large-scale metrology (which is not easy to perform with conventional CMMs).

Some innovative aspects of the system concern its online diagnostic tools. When dealing with measurement systems, good measurement diagnostics are crucial to applications in which errors can lead to serious consequences.

The diagnostics tool described in this chapter, which is based on the concept of the "reliability of a measurement," enables MScMS users to reject measurements which do not satisfy a statistical acceptance test with a given confidence coefficient.

After rejection, the operator is asked to perform the measurement again, changing the orientation/positioning of the probe; or, if necessary, to rearrange the beacons in the system network.

Preliminary results from the application of this online diagnostic tool reveal that it exhibits acceptable efficiency in preserving the system from measurement failures. However, in some cases the system requires the measurement to be repeated too many times, resulting in excessive duration of the measuring process.

Future work, as well as improvements in the power of the existing tools, will be aimed at enriching the MScMS control system by implementing additional tools that are able to steer the operator during measurement. For example, they could suggest the position of the probe in the measuring volume, or propose possible extensions to the network of beacons, or automatically filter and/or correct corrupted measurements.

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