Precision Engineering xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Precision Engineering

journal homepage: www.elsevier.com/locate/precision

A new methodology to design multi-sensor networks for distributed large-volume metrology systems based on triangulation

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ARTICLE INFO

Article history:
Received 23 March 2015
Received in revised form 29 May 2015
Accepted 1 July 2015
Available online xxx

Keywords:
Large-volume metrology
Distributed measuring system
Multi-sensor network
Triangulation
Network design
Network density

ABSTRACT

Distributed Large-Volume Metrology (LVM) systems are mainly used for industrial applications concerning assembly and dimensional verification of large-sized objects. These systems generally consist of a set of network devices, distributed around the measurement volume, and some targets to be localized, in contact with the measured object's surface or mounted on a hand-held probe for measuring the points of interest. Target localization is carried out through several approaches, which use angular and/or distance measurements by network devices.

This paper presents a new methodology to support the design of networks of devices, for distributed LVM systems based on triangulation (i.e., systems in which network devices perform angular measurements only). It is assumed that these systems use multi-sensor networks including two typologies of devices: some are accurate but expensive and other ones are less accurate but cheaper. The goal of the methodology is establishing a link between the following parameters: (i) density of network devices, (ii) mix between the two typologies of network devices, (iii) measurement uncertainty, and (iv) cost. The methodology allows to estimate the most appropriate density and mix between the two typologies of network devices, so that the distributed LVM system is conforming with the required measurement uncertainty and cost.

The methodology relies on a large number of simulated experiments, defined and implemented using a dedicated routine; feasibility and practicality is tested by preliminary experiments on a multi-sensor photogrammetric system, developed at Politecnico di Torino—DIGEP.

1. Introduction

The use of distributed systems for applications in the field of Large-Volume Metrology (LVM) is more and more diffused and consolidated [1]. Typical industrial applications concern assembly and dimensional verification of large-sized mechanical components, in which levels of accuracy of several tenths of millimetre are tolerated [2,3]. The reason behind the diffusion of distributed LVM systems is simple: arranging a portable measuring system around the object to be measured is often more practical than the *vice versa* [4,5].

In general, distributed LVM systems consist of: (i) a set of *network devices*, distributed around the object to be measured, (ii) some *targets* to be localized, generally in contact with the measured object's surface, or mounted on a hand-held probe for measuring the points of interest, and (iii) a centralized *data processing unit* (DPU), which receives local measurement data from network devices.

The localization of targets is carried out through three possible approaches:

- *Triangulation*, using the angles subtended by targets, with respect to network devices;
- *Multilateration*, using the distances between targets and network devices;
- *Hybrid techniques*, based on the combined use of angles and distances between targets and network devices.

In this paper we deal exclusively with distributed LVM systems based on triangulation; Fig. 1 provides a schematic representation of these systems: each *i*th network device (D_i) is associated with a local coordinate system $o_i x_i y_i z_i$ and is able to perform local angular measurements with respect to a target *P*; the aim of the measurement is localizing *P*, determining its spatial coordinates in the global Cartesian coordinate system *OXYZ*. In Fig. 1, four network devices (i.e., D_1 to D_4) are involved in the measurement, as it

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http://dx.doi.org/10.1016/j.precisioneng.2015.07.001
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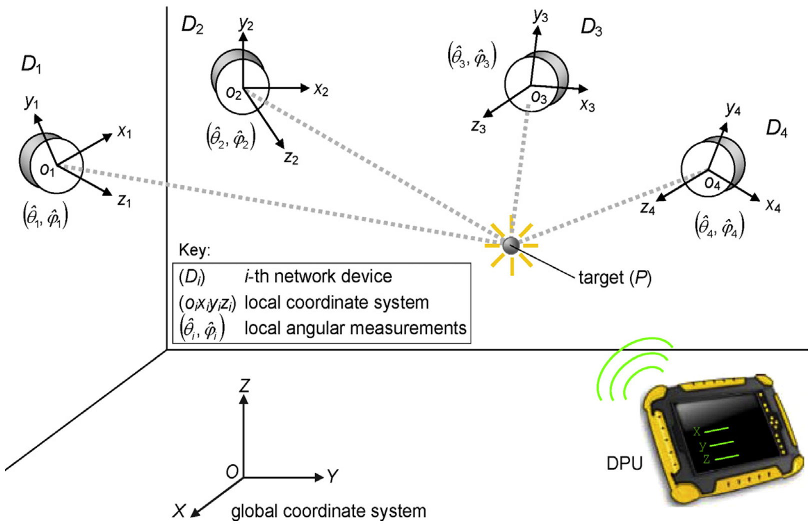

Fig. 1. Schematic representation of a generic distributed LVM system, based on triangulation.

is assumed that they all include P in their range of measurement. In general, the number of devices involved in the localization of a target depends on their mutual positioning/orientation and range of measurement. Each ith network device measures two angles, i.e., θ_i and φ_i, described in Section 2.

Network devices may differ in technology, measurement uncertainty, range of measurement and cost. For example, optical theodolites have uncertainty on angular measurements of a few hundredths of a degree, range of measurement of several tens of meters (with some constraints regarding angles) and cost of a few thousand €; the relatively recent rotary-automatic laser theodolites (R-LATs) have uncertainty on angular measurements of a few thousandths of a degree [6], range of measurement of about 20 m (with some constraints regarding angles) and cost around 50,000€; data related to photogrammetric cameras may fluctuate significantly, depending on their technical/metrological features, such as pixel resolution and frame rate.

When designing a network of devices for a distributed LVM system, two of the most important factors to consider are:

- *network density* (i.e., number of network devices per surface unit), since the uncertainty in target localization tends to decrease with the number of devices, which can "see" the target [7];
- *uncertainty of network devices* in measuring the angles subtended by targets. In general, the more technologically advanced and expensive the network devices, the lower their uncertainty in local angular measurements and, hence, that in target localization.

These factors could be both optimized by using dense networks of very accurate[1] devices, although this solution may result in high cost, in contrast to budget sustainability. A reasonable compromise to achieve good results, while limiting cost, is using multi-sensor[2] networks, which combine: (i) a relatively large number of not very accurate but cheap devices, for obtaining a good coverage of the measurement volume, and (ii) a relatively low number of accurate but expensive devices, for reducing the uncertainty in target localization.

Unfortunately, defining the optimal network density and mix between accurate and less-accurate devices is a difficult task, due to the complexity of the target localization problem and the fact that it can be influenced by several parameters related to network devices (e.g., range of measurement; uncertainty in angular measurement; uncertainty in their location/orientation, due to the calibration process, etc.) [5].

The aim of this paper is introducing a new supporting methodology to design multi-sensor networks for distributed LVM systems based on triangulation, assuming that these networks include two typologies of devices: some are accurate but expensive and other ones are less accurate but cheaper. The goal of the proposed methodology is establishing a link between four parameters: density of network devices (δ), percentage of accurate devices (p_A), measurement uncertainty, and cost. This will be done through a large number of simulated experiments, in which the former two parameters (δ and p_A) are varied and their influence on the latter two parameters is analyzed. In these simulated experiments, target localization is modelled through a consolidated mathematical model, which can be adapted to multi-sensor networks. In practical terms, the proposed methodology allows to estimate the optimal δ and p_A, so that the whole system is conforming with the required measurement uncertainty and cost.

The remainder of this paper is organized into three sections. Section 2 provides some basic concepts concerning the problem of the localization by triangulation and the mathematical model, which is used in the proposed methodology. Section 3 is divided into three parts: the first one describes the methodology, focusing on the multi-sensor network modelling; the second one provides a practical application to a distributed LVM system, which adopts two types of photogrammetric cameras; the third part checks the plausibility of the results of the previous application, on the basis of preliminary experiments, carried out at Politecnico di Torino—DIGEP. Section 4 summarizes the original contributions of this research, focussing on its implications, limitations and possible future developments.

2. The triangulation problem

Fig. 1 depicts a distributed LVM system based on triangulation, consisting of a number of network devices positioned around the measurement volume. $OXYZ$ is a global Cartesian coordinate system. Each ith device (D_i) has its own spatial position and

[1] The adjective "accurate" is used in a broad sense, denoting the ability of a network device to perform angular measurements with relatively low uncertainty; it is not necessarily related to the specific definition from the International Vocabulary of Metrology (VIM) [18].

[2] The adjective "multi-sensor" indicates that networks include devices, which – despite they all perform angular measurements – may differ in terms of technology, accuracy, range of measurement and cost.

Please cite this article in press as: Maisano D, Mastrogiacomo L. A new methodology to design multi-sensor networks for distributed large-volume metrology systems based on triangulation. Precis Eng (2015), http://dx.doi.org/10.1016/j.precisioneng.2015.07.001