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A novel calibration procedure for multiple large-volume-metrology instruments

Domenico A. Maisano[1], Luca Mastrogiacomo[1]

[1]*Politecnico di Torino, DIGEP (Department of Management and Production Engineering)*

domenico.maisano@polito.it

Abstract

Recent studies show that the combined use of various *Large-Volume-Metrology* (LVM) instruments can lead to a better exploitation of the available equipment and a systematic reduction in measurement uncertainty. Unfortunately, determining the spatial position/orientation of the sensors of the instruments in use through multiple instrument-dedicated calibration processes makes set-up time/cost increase significantly. This paper tackles this problem, developing a novel *global-calibration* procedure, which is based on the use of a unique artefact: an innovative hand-held *probe* with integrated inertial sensors and assorted types of targets that can be customized depending on the LVM instruments in use. An initial acquisition stage, in which the probe is repositioned several times in the measurement volume, is followed by a data-processing stage, in which an *ad hoc* mathematical/statistical model is adopted. The proposed procedure makes it possible to estimate the uncertainty in the position/orientation of the sensors of the instruments in use, taking the uncertainties of the input variables into account.

Keywords: Metrology, Sensor, Calibration, Probe.

1. Introduction

Typical industrial applications in the field of *Large-Volume Metrology* (LVM) are concerned with the dimensional verification and assembly of large-sized mechanical components. These applications generally involve technologically advanced and expensive measuring instruments, which may require time consuming set-up/calibration operations [1-3].

LVM instruments – e.g., laser trackers, laser radars, photogrammetric systems, rotary-laser automatic theodolites (R-LATs), etc. – are usually equipped with *sensors* that are able to perform local measurements of the *distances* and/or *angles* subtended by some *targets* within the measurement volume.

Recent studies show that the combined use of various LVM instruments can lead to a better exploitation of the available equipment and a systematic reduction in measurement uncertainty [4]. The combination of multiple LVM instruments can be seen as a single "macro-instrument" consisting of a *network* of sensors of different nature.

In addition, a novel multi-target hand-held *probe* has been recently developed [5]; depending on the LVM instruments in use, this probe can be equipped with assorted types of targets and integrated inertial sensors.

Before any LVM measurement task, the so called *sensor-network calibration* is needed, that is to say estimating: (i) the *extrinsic* parameters of sensors, i.e., their spatial position and orientation, and (ii) their *intrinsic* parameters, i.e., parameters concerned with other specific technical characteristics (e.g., focal distance or lens distortion of photogrammetric sensors, wavelength or air refractive index of interferometric sensors, etc.).

While the determination of intrinsic parameters can be performed from time to time, as long as conditions of the measurement instruments and environment are relatively stable, the determination of extrinsic parameters should be performed whenever the sensor-network layout is changed.

When using combinations of various LVM instruments, several independent instrument-dedicated calibration processes – which are based on the use of specific artefacts, acquisition processes and optimization algorithms – are generally performed. The purpose of this paper is to develop a unique *global-calibration* procedure to determine the extrinsic parameters of various network sensors, in a single acquisition process. The aforementioned multi-target probe can be used for data acquisition and to provide metrological traceability to the measurement unit of length.

The remainder of this paper is divided into three sections: Sect. 2 formalizes the problem and illustrates the global-calibration procedure; Sect. 3 shows some preliminary results, while Sect. 4 summarizes the main advantages of the proposed procedure and possible ideas for future research.

2. Methodology

Let us consider (i) a generic combination of LVM instruments with assorted network sensors, (ii) a hand-held probe with multiple targets and integrated inertial sensors (i.e., two-axis inclinometer and compass, see Figure 1), and (iii) a number of acquisitions, in which the probe is repositioned several times within the measurement volume, and distance/angular measurements of network sensors (with respect to probe targets) and angular measurement of the probe integrated inertial sensors are collected.

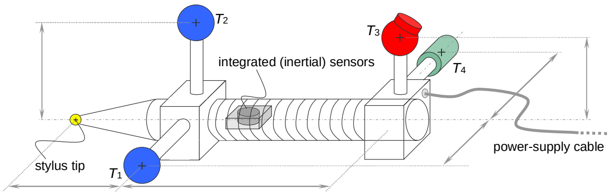

Figure 1. Qualitative example of multi-target hand-held probe. In this specific configuration, the probe has integrated inertial sensors and three typologies of targets: (T_1 and T_2) two reflective spherical markers for photogrammetric sensors, (T_3) a spherically mounted retroreflector (SMR) for laser trackers, and (T_4) a cylindrical target for R-LAT sensors.

Figure 2 shows the input/output variables of the problem, which may depend on several features, such as: (i) number/typology of LVM instruments in use and relevant sensors, (ii) number and typology of probe targets, (iii) communication range of the sensors/targets in use, and (iv) number of probe acquisitions.

We remark that all the variables of the problem are dispersed and therefore associated with specific uncertainties. Since (some of) these variables can be correlated with each other, their variability can be expressed through (co)variances.

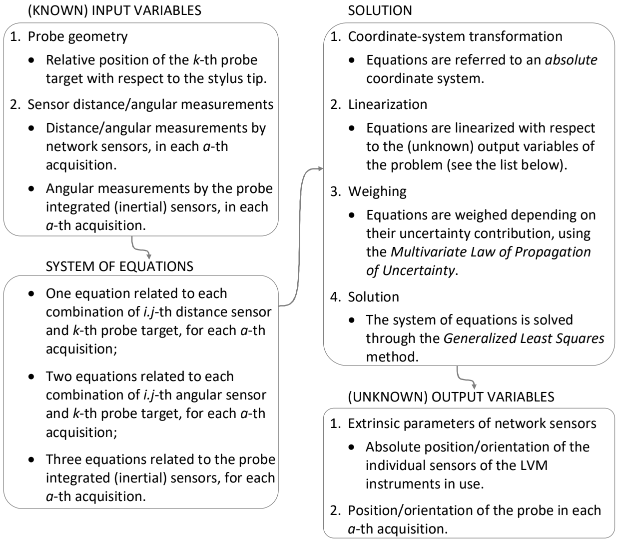

Figure 2. Scheme of the global-calibration procedure.

The proposed global-calibration procedure is based on several steps (see Figure 2):

- Formulation of a system of equations;
- Introduction of suitable transformations to refer local Cartesian coordinate systems (e.g., those related to network sensors, probe, etc.) to a single *absolute* coordinate system.
- *Linearization* of these equations with respect to the unknown variables of the problem;
- Weighing of the equations, based on the uncertainty contributions of the variables contained therein, through the *Multivariate Law of Propagation of Uncertainty* (MLPU).
- Solution of the system of equations through the *Generalized Least Squares* (GLS) method and determination of the unknown variables (with relevant uncertainties).

The global-calibration problem can be formalized as:

$$\boldsymbol{A} \cdot \boldsymbol{X} - \boldsymbol{B} = \boldsymbol{0}, \tag{1}$$

where $\boldsymbol{X}$ is a column vector containing the unknown variables. When the number of probe acquisitions is large enough, this system of (linearized) equations is likely to be overdefined and can be solved through the GLS method, giving greater weight to the contributions from equations that produce less uncertainty and *vice versa* [6, 7]. A weight matrix ($\boldsymbol{W}$) can be constructed by applying the MLPU to the system in Eq. 1, with reference to the input variables affected by uncertainty (see description in Figure 2), which are aggregated into the column vector ξ. $\boldsymbol{W}$ can be determined as:

$$\boldsymbol{W} = \left[\boldsymbol{J} \cdot \Sigma_{\xi} \cdot \boldsymbol{J}^T\right]^{-1}, \tag{2}$$

where Σ_{ξ} is the covariance matrix of ξ and can be defined using data resulting from preliminary *ad hoc* experimental tests and/or technical documents relating to the instruments/artefacts in use.

A final estimate of $\boldsymbol{X}$ can be obtained as:

$$\hat{\boldsymbol{X}} = \left(\boldsymbol{A}^T \cdot \boldsymbol{W} \cdot \boldsymbol{A}\right)^{-1} \cdot \boldsymbol{A}^T \cdot \boldsymbol{W} \cdot \boldsymbol{B}. \tag{3}$$

The uncertainty of $\boldsymbol{X}$ is contained in the covariance matrix $\Sigma_{\boldsymbol{X}}$, which can be determined as:

$$\Sigma_{\boldsymbol{X}} = \left(\boldsymbol{A}^T \cdot \boldsymbol{W} \cdot \boldsymbol{A}\right)^{-1}. \tag{4}$$

3. Preliminary results

Several simulated experiments have shown that the global-calibration procedure tends to converge quickly to the correct solution, for any sensor-network and probe-target configuration. It is essential that the number of probe repositionings in the acquisition process is large enough, so that the number of equations is greater than the number of unknowns (see Figure 2). In addition, when inverting the matrices in Eqs. 2 and 3, it is recommended to use a *Singular-Value-Decomposition* (SVD) approach (e.g., Moore-Penrose pseudoinverse [6]), to avoid matrix conditioning problems.

The accuracy in the resulting position/orientation of network sensors is generally related to that in their distance/angular measurements. Consequently, the more accurate the network sensors, the more accurate their location.

4. Conclusions

The proposed procedure is *versatile*, since it can be adapted to any type of LVM instrument with sensors performing distance/angular measurements with respect to targets. It is *practical*, since it allows to locate the network sensors through a single acquisition process, using a special artefact (i.e., multi-target hand-held probe) and avoiding multiple instrument-dedicated calibration processes. It is *efficient*, as it is based on a system of linearized equations, and *effective*, as the equations are weighted with respect to the uncertainty contributions of the input variables. It also makes it possible to determine the position/orientation of network sensors.

The proposed global-calibration can greatly encourage the combined use of LVM instruments of different nature, which is nowadays relatively limited, due to the lack of suitable hardware tools and support methods.

Regarding the future, we plan to perform further (real and simulated) experiments to prove the superiority of the global-calibration procedure with respect to traditional instrument-dedicated calibration processes, from several perspectives (e.g., accuracy in the location of the sensor network, time and simplicity of execution, etc.).

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