euspen's 16th International Conference & Exhibition, Nottingham, UK, May 2016
www.euspen.eu

A high-accuracy, self-calibrating and traceable coordinate measurement system

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Abstract

Two questions which users of portable large volume measuring systems often ask the National Physical Laboratory (NPL) are: 'How good is my instrument?' and 'what are the uncertainties associated with my measurements?' These are fundamental questions which are difficult to answer and failure to answer them or providing an incorrect or incomplete answer can have expensive consequences for manufacturing industry. At NPL we felt an instrument was needed which would inherently answer these questions with every measurement. We are therefore developing a coordinate measurement system that is inherently self-calibrating, calculates in-process uncertainty estimates, and has integral traceability to the SI metre. These attributes are achieved using frequency scanning interferometry which is used to make absolute distance measurements from multiple sensors to multiple targets and multilateration which is used to calculate target coordinates from distance data along with uncertainty estimates. The prototype system operates in a volume of up to 10 m x 10 m x 5 m with a fractional range uncertainty of 2 x 10^{-6} (k=1) and a coordinate uncertainty on the order of 5 x 10^{-6} (k=1).

Keywords: Coordinate metrology, frequency scanning interferometry, multilateration, self-calibration

1. Introduction

Accurate, traceable measurement is a key requirement for efficient manufacturing and assembly. For large sized components, structures, or facilities, large volume metrology (LVM) tools such as laser trackers, laser radar, photogrammetry, laser scanners, theodolites, total stations and hydrostatic levels, are required [1]. Typical measurement ranges of these tools are from around one metre to several tens or hundreds of metres and they are used in a wide range of applications such as aerospace manufacturing and assembly, civil engineering, particle accelerator alignment for science and beam therapy systems, and manufacturing of energy generation systems (civil nuclear, wind and fusion research).

Apart from photogrammetry (specifically multi-camera videogrammetry), which can achieve an uncertainty of around a few parts in 10^5, all these LVM tools measure a single point in space at one time, though rapid sequential measurement is possible using e.g. laser scanners and laser radar. The relative uncertainty of the measured points, based on manufacturer's specifications, ranges from around 5 × 10^{-6} (static target measured using a laser tracker), to 5 × 10^{-5} (the most accurate laser scanners).

Currently no instrument provides on-line uncertainty estimates based on the actual measurement data, and calibration is only performed periodically with limited "field checks" being performed more frequently as a means of evaluating measurement capability.

These limitations lead to questions being asked about the validity of calibration and uncertainty of measurements made on the shop floor.

At NPL we are developing a coordinate measurement system to address these questions, which operates over a 10 x 10 x 5 m volume with an estimated fractional coordinate uncertainty of 2 × 10^{-6}. The system is self-calibrating with compensation for systematic errors, calculates in-process uncertainty estimates, and has inherent traceability to the SI metre.

These attributes are achieved using frequency scanning interferometry to make absolute distance measurements between multiple sensors and multiple targets and multilateration to calculate coordinate positions and provide a self-calibration capability [2-4] with rigorous uncertainty estimates calculated in accordance with the ISO GUM [5].

The rest of this paper describes the prototype instrument being developed at NPL. In section 2 of this paper we outline the operating principles. Section 3 describes the prototype instrument. In section 4 we outline tests, the results of which will be presented in the final paper.

2. Operating principles

This section describes the basic operating principles of FSI and multilateration.

2.1. Frequency Scanning Interferometry

The absolute distance between target and sensor is measured using frequency scanning interferometry (FSI) [4]. Light from a continuously tuneable laser is fibre-fed to a sensor. Some of the light is intentionally reflected by the end of the fibre, acting as the reference signal, while the rest of the light is projected towards a target. Some of the light is reflected back from the target into the fibre and interferes with the reference signal. The intensity of the interference signal produced on a detector, $I(t, \tau)$ is described by Equation 1. The frequency of the interference signal is a function of the time of flight, τ, between the target and sensor, and the rate of tuning of the laser, α.

$$I(t,\tau) = A \cdot \cos\left[2\pi\left(\alpha t\tau + f_0\tau\right)\right] \quad (1)$$

Here, f_0 is the optical frequency of the swept laser at time t = 0, A is the magnitude of the signal. This signal has a frequency component, f_{beat}, that is related to the target distance, D, by Equation 2,

$$D = c\frac{f_{beat}}{2\alpha} \quad (2)$$

where *c* = speed of light.

Multiple targets can be measured simultaneously by projecting the measurement beam into a volume, and analysing the frequency spectrum of the interference signals received.

2.2. Multilateration

The coordinates of the targets and sensors are calculated from the absolute distance measurements using multilateration. Multilateration is a method of determining coordinates of a target point by measuring range to the target point from three or more other sensor positions. If the sensor positions are known accurately, then only three sensors are required. However, if at least 6 targets are measured from a minimum of 4 sensors, it is possible to calculate the location of both the targets and sensors without any prior information.

To illustrate this self-calibration ability, consider a number, *N*, of range measuring devices located at positions $\boldsymbol{T}_i = (xt_i, yt_i, zt_i)$, $(1 \leq i \leq N)$, and a number, *M*, of targets located at positions $\boldsymbol{P}_j = (xp_j, yp_j, zp_j)$ $(1 \leq j \leq M)$. The distances between the i^{th} measurement device and the j^{th} target, D_{ij}, can be expressed as,

$$\left|\boldsymbol{T}_i - \boldsymbol{P}_j\right| = D_{ij} \quad (3)$$

If we define, for example, $\boldsymbol{P}_0 = (0, 0, 0)$, $\boldsymbol{P}_1 = (xp_1, 0, 0)$ and $\boldsymbol{P}_2 = (xp_2, yp_2, 0)$, *i.e.* arbitrarily constrain these three target points to the origin, *x*-axis and *x-y* plane respectively, then Equation 3 can be solved provided $N \geq 4$ and $M \geq 6$.

In practice, $M >> 6$ and the equations are solved using standard non-linear least-squares analysis. If the observations, D_{ij}, are weighted by weights, $w_{ij} = 1/u(D_{ij})$, where $u(D_{ij})$ is the estimated uncertainty in D_{ij}, then the covariance matrix derived from the least-squares analysis contains the variance of each fitted parameter.

The simple model expressed by Equation 3 can be extended to include systematic effects within the measurement system and these parameters and their associated uncertainty estimates can also be determined from the covariance matrix.

Furthermore, if the absolute distance measurements are traceable to the SI metre and have known uncertainty, this traceability is retained in the coordinate measurements.

3. Prototype instrument

In [4] we proposed a simple sensor that used a diverging lens to broadcast a conic beam into the measurement space to illuminate multiple targets. This embodiment has the drawback that it is very inefficient in terms of optical power usage. This limits the practical operating volume to around 1 m^3.

In this paper we present a new sensor design that overcomes this problem by splitting the available optical power into multiple beams, each of which is automatically directed to an individual target. The targets are glass spheres made of glass with a refractive index of two.

The new sensor design uses a spatial light modulator (SLM). A camera integrated on the optical axis is used to identify and locate the off-axis angular location of the targets so that the SLM can be programmed to direct FSI beams to the targets.

Traceability to the SI is achieved using a HCN gas absorption cell as a frequency reference to determine the laser tuning rate, α, in Equation 1.

The prototype sensor is shown in Figure 1.

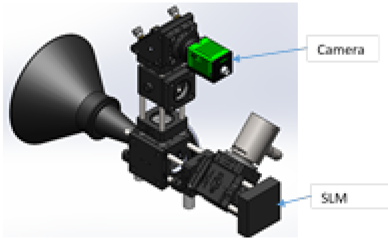

Figure 1. Prototype sensor head developed at NPL for multi-beam FSI measurements. A camera system is employed to detect where in the SLM FoV the targets are located. Both the camera and SLM share a similar optical axis to ensure easy transformation between the two 2D coordinate systems.

Figure 2 shows an example of a typical measurement application with four sensors surrounding the workpiece.

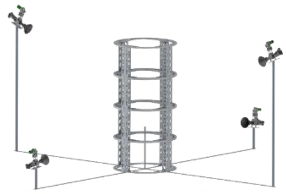

Figure 2. An example setup showing four sensor heads measure glass targets mounted onto the structure being measured.

4. Planned Tests

In the poster, we will present an extension to the basic multilateration model described by Equation 3, which takes into account the major systematic errors of our sensor. We will demonstrate that these systematic errors can be determined and present an uncertainty analysis that shows that a target coordinate uncertainty on the order of 5 x 10^{-6} (k=1) can be achieved.

5. Conclusions

A new novel high-accuracy, self-calibrating coordinate measurement system with inherent traceability to the SI has been proposed. The operating principals of FSI to measure absolute distances and multilateration to provide coordinate measurements and uncertainty estimates have been described. The fact that the instrument is able to provide the user with coordinates that are traceable to the SI and are provided with rigorously evaluated measurement uncertainty represents a unique capability that answers the often asked questions posed in the abstract.

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