A VERIFICATION METHODOLOGY FOR PHOTOGRAMMETRY SYSTEMS

T.A. Clarke[1], X. Wang[1] and A.B. Forbes[2]

[1]*Optical Metrology Centre, UK*
[2]*National Physical Laboratory, UK*

ABSTRACT

Large volume metrology systems such as Laser trackers and photogrammety systems are used in high value applications but the infrastructure for non-experts to verify the capability of these systems is poor. This paper will discuss the extension of the ISO 10360-2 standard for CMM's to photogrammetry systems. The method adopted follows the scheme developed and tested for laser trackers presented at CMSC in 2000. In summary the method involves:

- establishing the model for the system under test,
- developing a methodology that will analyse the performance of each parameter in the system,
- checking the systems measurement error against the predicted accuracy from the model

The method is illustrated by practical test results.

1 INTRODUCTION

This paper is concerned with verification procedures for large volume metrology systems [1]. Any such procedure will involve value judgements based on various competing requirements. For instance, however desirable it might be to have thousands of measurements it may only be possible to take a few hundred. Some key issues are the following:

- **Practicality** - any procedure has to be carried out within a time period acceptable to the end-user and the physical requirements and cost must not be prohibitive.
- **Confidence** - the procedure should have sufficient redundancy to ensure statistical reliability such that no significant shortcomings of the measurement systems go undetected.
- **Transparency** - the user should be able to easily understand the procedure, interpret the results and be able to make valid inferences about measurements made in similar working volumes and conditions.

The main components of the verification methodology described below are as follows: (1) a mathematical model of the nominal system behaviour described in terms of statistical properties of the measurement sensors and the system configuration, (2) estimation of the uncertainty in the distance between any pair of points in the working volume derived from the mathematical model, (3) repeated measurement of a length artefact, (4) comparison of the measurement data with the uncertainty model, and (5) derivation of a statement of system performance. In this paper, this methodology will be illustrated for a photogrammetric system. The methodology can also be applied to theodolite and portable arm CMM systems, for example, results of applying the scheme to Laser Trackers were presented at CMSC 2000.

2 THEORY

The verification of the length measuring capabilities of a co-ordinate measuring machine (CMM) according to the principles of ISO 10360-2 [4] is based on the following components:

- a statement of the length measuring capability of the CMM,
- calibrated length artefacts,
- measurement of the length artefacts,
- comparison of the estimates of the lengths derived from the CMM measurements with the corresponding calibrated values.

The scheme is quite generic and can be adapted to verify the length measuring capability of any co-ordinate measuring system (CMS). The effectiveness of the scheme depends largely on (a) the appropriateness of the statement of capability, (b) the adequacy of the measurement strategy and (c) the availability of suitable length artefacts.

2.1 Statement of capability

For conventional CMMs, the statement of length measuring capability takes the following form:

> Given an artefact of calibrated length L, the estimate of its length $\hat{L}$ derived for measurements should depart from its calibrated value by no more than $A + B/L$, i.e.,
>
> $$\left|L - \hat{L}\right| \leq A + B/L.$$

Thus, the capability is specified by the two constants A and B. That the above equation does not involve the location of the artefact within the working volume reflects the isotropic behaviour of CMMs: the errors in one area of the CMM are comparable with those in any other area.

A more general statement of length measuring capability is:

> Given a length artefact of calibrated length L, the estimate of its length $\hat{L}$ derived for measurements $\mathbf{x}_L$ and $\mathbf{w}_L$ satisfies
>
> $$\left|L - \hat{L}\right| \leq A(\mathbf{x}_L, \mathbf{w}_L),$$
>
> where $A(\mathbf{x}_L, \mathbf{w}_L)$ is a predefined function.

The dependency of the *capability function* A on location allows for any anisotropic behaviour to be taken into account.

We now describe a general approach for defining suitable capability functions for large volume measuring systems. The estimate of a target coordinates $\mathbf{x}_j = \mathbf{x}(\mathbf{u}_j, \mathbf{b})$ by a CMS depends on two sets of information a) the *sensor readings* $\mathbf{u}_j$ and b) the *configuration parameters* $\mathbf{b}$. For a conventional CMM, the sensor readings are the scale measurements; for a laser tracker they are the two angle measurements and the interferometric displacement measurement; for a photogrammetric system, the co-ordinates of the target on a two-dimensional image. The individual sensor readings are associated with a single target location. The configuration parameters are those that influence a number, or all, of the targets estimates. For a conventional CMM, they can include the probe offset and diameter and parameters specifying the error correction map; for a laser tracker they include the parameters specifying the tracker location and orientation and the offset associated with the interferometric displacement, for example; for a photogrammetric system, they specify the camera locations, orientations and optical characteristics.

The target estimation function $\mathbf{x}_j = \mathbf{x}(\mathbf{u}_j, \mathbf{b})$ may be straightforward and explicitly defined, as in the case of a conventional CMM or a single laser tracker, or defined implicitly as the solution of a nonlinear system of equations as in the case of theodolites, photogrammetry and multiple laser trackers. In all cases, however, the nominal behaviour of the system can be defined completely in terms of the geometry of the system (i.e., the position of the measuring stations and targets) and the target estimation function can be derived from geometric principles.

The uncertainty in the target estimates will depend directly on the uncertainty in the sensor measurements and the estimates of the configuration parameters. A statement of the uncertainty of the sensor measurements can be converted into a statement of the uncertainty in the target location using the laws of propagation of uncertainties [3]. For example, if $\mathbf{u}_j = (u_{j,1}, \ldots, u_{j,p})^T$ and $u_{j,q}$ has variance σ_q^2, then the variance $\sigma_{j,k}^2$ of the *k*th component $x_{j,k}$ of $\mathbf{x}_j$ is given by

$$\sigma_{j,k}^2 = \sum_q \left(\frac{\partial x_{j,k}}{\partial u_{j,q}} \right)^2 \sigma_q^2 .$$

(These variances can be visualised as error ellipsoids centred at the target location.) In this way, from a statistical model for the sensor measurement and configuration parameters we can derive an estimate of the standard uncertainty $u_{\mathbf{b}}(\mathbf{x}, \mathbf{w})$ of the distance between any two points $\mathbf{x}$ and $\mathbf{w}$ in the working volume of the CMS. The subscript $\mathbf{b}$ indicates the function depends on the configuration of the system. The capability function can then be expressed as a suitable multiple of u:

$$A(\mathbf{x}_L, \mathbf{w}_L) = K u_{\mathbf{b}}(\mathbf{x}_L, \mathbf{w}_L) .$$

2.2 Comparison of measurements with capability statement

The derivation of the capability function described above is based on a statistical model of CMS behaviour. It is therefore appropriate that the comparison of measured lengths with their calibrated values is also statistically based. The function $u_{\mathbf{b}}(\mathbf{x}, \mathbf{w})$ gives the standard uncertainty in the measurement of length from $\mathbf{x}$ to $\mathbf{w}$, i.e., the expected deviation in the length measurements at these locations from the true value. Assuming the errors are normally distributed, we would expect approximately 95% of these measurements to be within $2u_{\mathbf{b}}(\mathbf{x},\mathbf{w})$ of the calibrated value. If we expect the errors at different locations to be largely uncorrelated (and normally distributed) then given measurements $\hat{L}_j$ of lengths L_j at pairs of locations $(\mathbf{x}_j,\mathbf{w}_j)$, we expect

$$\left|L_j - \hat{L}_j\right| \leq 2u_b(\mathbf{x}_j,\mathbf{w}_j),$$

to hold for 95% of the measurements. In general, the degree of conformance is measured by the actual deviation of the measured lengths from their calibrated values compared with the expected deviation described by the capability function. The comparison can be defined to take into account correlation in the measurements and uncertainty in the calibrated values of the length artefacts.

3. VERIFICATION OF A PHOTOGRAMMETRIC SYSTEM

3.1 The specification for a photogrammetric system

A stereo photogrammetry system has been chosen to illustrate the methodology, extension to single camera photogrammetry can also be made. A model for the system is used to predict the non-isotropic behaviour and length measurements are compared with the predictions. However, in the case of photogrammetry there is no commonly agreed means of specifying the performance. Manufacturers often provide a one or two sigma measurement precision as a proportion of the largest dimension of a measurement volume, e.g., 1 part in 100,000. The capability function $A(\mathbf{x},\mathbf{w})$ has a complex form, depending on the position of the cameras and the number of views of a given target. However the general principles described in section 2 can be applied to derive a capability function. A photogrammetric camera acts as an angle measurement device and the commonly accepted internal model assumes equal accuracy at all points in the image plane. An internal measure of image accuracy is provided by what are termed "image residuals", the differences between the original image observations and the projections from object to image space (using the photogrammetry system model) of the 3-D estimates of the object targets. The standard deviation of these residual errors has been chosen as the prime indicator of system performance on which the uncertainty model is based.

3.2 Verification strategy

The basic scheme implemented for verification of photogrammetry systems is to use reference lengths comparable with the dimensions of the measurement envelope of the system being tested. The reference lengths can either be physical, consisting of an artefact with at least five targets in known positions, or *virtual,* being the measured location of a single target moved to various positions. The auxiliary measurement system might be a CMM, a laser tracker or an interferometer. The real or virtual reference lengths are position in a number of locations and measuring lines within the working volume of the measurement system, for example, along its X, Y and Z axes and various diagonal and compound diagonals.

3.3 Data collection

The configuration of the stereo system with respect to the virtual length artefact is illustrated for one of the configurations in Figure 1.

Figure 1. Configuration for verification

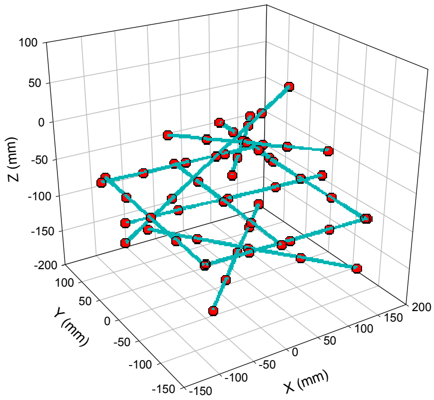
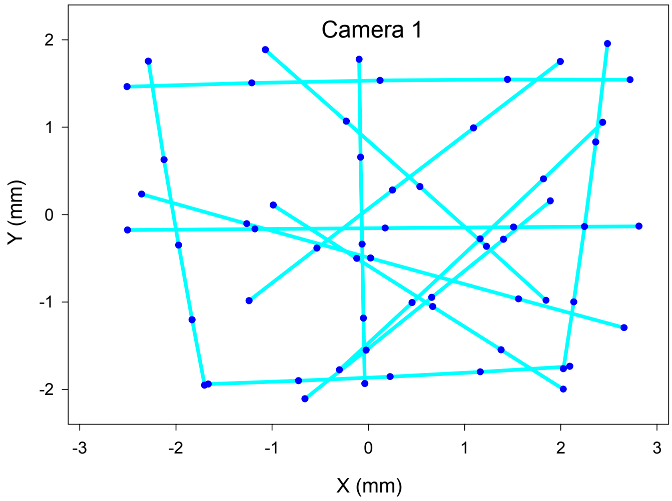


Figure 2. Arrangement of virtual length artefacts

In each configuration, measurements of a number of traceable lengths were collected. The 3-D arrangement for the various lengths is illustrated in Figure 2. The measurement envelope for the system under test is not a simple shape as it is defined by the mutual overlap of the two camera views. At each of the measurement locations, illustrated by the blob on the line, the interferometer reading was noted along with the 3-D measurement of the target using the photogrammetry system. To illustrate the fact that this strategy is a good test of the camera calibration Figure 3 illustrates the position of the target and the line of the virtual artefact measurements.



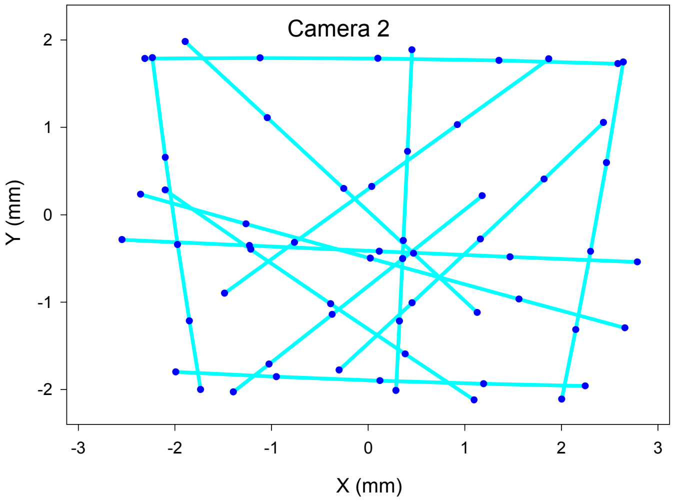


Figure 3. Position of the targets and virtual length artefact in both images.

The 3-D co-ordinates of the target at each location (computed by intersection with known camera exterior parameters) were used to calculate the distances between adjacent two locations. If the absolute differences between the measured distances and the traceable lengths are less than estimated uncertainty of the distances the system is verified. If the stereo system specification is verified, the method of specifying the performance of photogrammetry systems can be also be considered valid. The specification can then be used to predict the performance of the system in other configurations. The results of the verification are illustrated in the following figure.

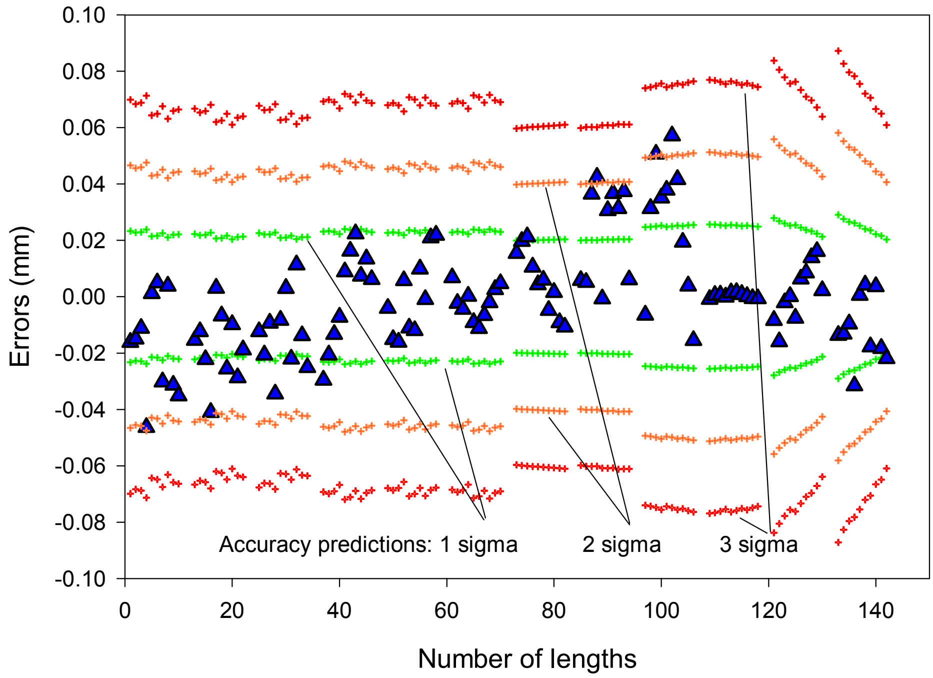


Figure 4. Verification results from all measurements

If enough samples are taken and a normal distribution of errors is expected then some 68% of errors will be within 1 sigma of the mean, 95.5% within 2 sigma and 99.7 % within 3 sigma. Given the distribution of errors in the example, this system passed the verification test.

3.4 Results of the verification experiment

The verification methodology has been applied to various stereo camera systems. The results showed that the method was sufficiently sensitive to indicate whether these systems were inside the specification or not. The work also confirmed that the approach adopted for specifying the performance of these systems was valid.

4 CONCLUSIONS

The verification methodology discussed in this paper extends the principles of the ISO 10360-2 standard for CMM's. The following advantages of the scheme can be outlined:

- The methods are based on appropriate models of system behaviour that properly take into account the anisotropic behaviour and its dependence on system configuration.
- The models of nominal behaviour for each system can be derived from relatively simple principles of geometry and statistics.

- The measurements involving the traceable lengths provide sensitive measures of the performance characteristics of each system.
- Analysis of the results is straightforward, rigorous and can be implemented in a simple software module.

The methods developed are direct and practical and could form the basis for an extension of the ISO 10360-2 scheme to large volume measuring systems, providing the required infrastructure to support quality control in many high value industries.

5 ACKNOWLEDGEMENTS

The funding for the research has been sponsored by the UK Government EPSRC Grant No. GR/ L89310 and the Department of Trade and Industry's National Measurement System Programme for Length.

6 REFERENCES

[1] Clarke, T.A., Wang, X., Forbes, A.B. & Cross, N.R. The case for a consistent method of verifying the performance of large volume metrology systems, *Co-ordinate Measurement Systems Committee Conference*, Detroit, USA, August 2000.

[2] Corta, R, et al., *A large reference artefact for CMM verification*, NPL Report CLM 6, National Physical Laboratory: Teddington, 1998.

[3] Cox, M.G., Forbes, A.B. & Harris, P.M. *Software Support for Metrology Best Practice Guide No. 4: Discrete Modelling*, National Physical Laboratory: Teddington, 2000.

[4] ISO: *ISO 10360-2. Co-ordinate metrology part 2: performance assessment of co-ordinate measuring machines*, ISO: Geneva, 1993.