The case for a consistent method of verifying the performance of large volume metrology systems

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1. Introduction

A method for verification of the performance of conventional co-ordinate measuring machines (CMM's) has been well established and is defined in the ISO 10360-2 standard (ISO 1995). This specifies how measurements of a set of traceable lengths (for example, step gauges, length bars, etc.) can be used to verify whether the length measuring capabilities of a given instrument is within the manufacturer's specification. Large volume measurement systems such as laser trackers, photogrammetry, portable arms, and metrology driven machines, are not specifically addressed by the ISO 10360-2 standard. However, large volume measurement systems are increasingly being used in high value processes and the requirement for verification procedures for such systems has been clearly identified. (Brown, 1999; Sandwith, 1995; Luhmann & Wendt, 2000).

This paper makes the case for a consistent method for verification of large volume measurement systems, using the laser tracker as an example. The methodology described is also being applied to photogrammetry systems and in principle can be applied to any large volume measurement system. The aim is to produce a verification methodology that provides valid measures of performance across a range of systems, rather than a collection of *ad hoc* procedures that provide limited or even misleading information.

2. The problem

Most portable large volume measurement systems do not have simple characteristics. For instance:

- laser trackers have angle errors that are much larger than the interferometric distance errors,
- photogrammetric systems have varying accuracy depending on the range, the number of images used, and from where the images are taken, and
- a portable arm CMM can measure to the same point with a range of arm positions.

For quality control purposes, an accepted procedure for verification of performance of a measurement system is required. Without such a procedure, it is not clear that an instrument is performing to its specification and therefore whether it is capable of being used to measure a part to within some percentage of its product tolerance. The ISO 10360-2 standard provides a universal scheme for verification of the length measuring capabilities of CMM's. It is based upon the measurement of calibrated lengths that are positioned within the working volume of a machine. The method is widely accepted and understood. However, the method relies on the fact that for virtually all CMM's, the measurement accuracy is nominally constant throughout the working volume – i.e., *isotropic* behaviour. This assumption is not true for many large volume measurement systems. Their measuring capabilities can vary significantly over the working volume and with respect to measurement lines within the working volume. A direct application of an ISO 10360-2 procedure could give an overly pessimistic or optimistic assessment, depending on how it was implemented and in general provide the user with no information about the *anisotripic* behaviour of the system.

3. The proposed solution

It is proposed that the general features of the ISO 10360-2 standard relating to establishing traceability via the measurement of calibrated lengths should be understood and retained. The specification of performance for a CMM predicts how well the CMM measures a length within its working volume in terms of an easily calculated tolerance. The difference between the measured length and calibrated length is compared with this tolerance. The extension to large volume measuring systems is based on precisely the same principles, only different models of the measurement systems are used to provide the appropriate tolerances. By using these models, the variation in system behaviour throughout its working volume can be taken into account. The same models can also be used to determine whether the system is fit for a specific measurement task using a given measurement configuration. The definition of verification procedures involves value judgements based on various competing requirements. The most important issues are:

- **Practicality** - any procedure has to be carried out within a time period acceptable to the end-user and the physical requirements and cost must be reasonable.
- **Confidence** - the procedure should have sufficient redundancy to ensure that the results can be obtained with a reasonable level of confidence and that no significant shortcomings of the measurement systems go undetected.
- **Transparency** - the user should be able to easily interpret the results obtained from the verification procedures and be able to make valid inferences about measurements made in similar working volumes and conditions.
- **Software –** the verification procedure relies on predicted behaviour based on a model of the measurement behaviour. These calculations will require software as they are likely to be too complex to be performed manually. The performance of the software itself will need to be verified. The comparison of the actual measurement with the prediction remains a simple task, as with ISO 10360-2.
- **Measurement of calibrated lengths -** It is assumed that like ISO 10360-2, the measurement of standard lengths provides the majority of the information required for verification.

4. Practical development

4.1. Introduction

City University, the National Physical Laboratory and leading aerospace companies in the UK are collaborating in a national project to develop a consistent and proven scheme for verifying the performance of large volume measurement systems. There are three key features of the work:

- Modeling of the characteristics of measurement systems in generic terms. Models for photogrammetry, theodolite and laser tracker systems have been produced.
- Use of a large length artifact. The National Physical Laboratory have developed a carbon-fibre lightweight length artifact suitable for use with both conventional and laser trackers/portable CMM's (Corta, *et al.* 1998).
- Development of specific procedures and software to perform verification. By considering the mathematical model for each system it is possible to determine a suitable strategy for verification. Stochastic analysis leads to an understanding of the relationship between the number of measurements taken and the effect on the confidence factor.

4.2. Creation of an appropriate mathematical model

The mathematical model developed to describe a measuring system would ideally be as generic as possible and cover all instruments of the same type. For example, the generic model for a laser tracker is based on two angle sensors and a distance sensor. The statistical model for the tracker includes parameters to specify absolute and distance dependent uncertainties. In practice, the generic model will need to be tailored to a particular instrument. For example, the contribution to the error model associated with a calibrated offset distance ("bird-bath" error) associated with a laser tracker may have to be treated differently for different systems. Since the instrument performance is to be verified against the manufacturer's stated performance specification, it is important that the model adequately reflects the system characteristics. If a manufacturer's specifications are arbitrarily defined without good physical reasons, it may be important to influence the manufacturer to use a common method of specifying performance. In principle, a specification of the uncertainty (or tolerance) associated the measured distance between any two points as a function of those two points is all that is required to allow an ISO 10360-2-type verification.

4.3. Development of a verification methodology for laser trackers

Analysis of the mathematical model derived from the specification of a Leica laser tracker led to the development of procedures and physical requirements for assessing the performance of this system. The system capability is specified in terms of statistical models associated with the angle and distance sensors. In order to test against these specifications, it is important to design measurement strategies that single out the performance of each sensor. For instance, the procedure for estimating the performance of the interferometer should largely be independent of the influence of the angle encoders.

It is also important that the influence of the environmental factors such as temperature and pressure are accounted for according to the manufacturer's guidelines (Sandwith, 2000). It is expected that the verification trial will take place in a typical operating environment where temperature gradients and changes in temperature will be similar to when the tracker is used in practice.

The following procedure illustrates the procedures that were followed in the latest series of tests. It is stressed that these are only draft procedures but they do embody the main principles that are likely to be required in practice.

Verification of Interferometer and ADM performance

(a). Set up the Tracker so that it is looking along the axis of the artefact and can see all of the targets without having to be tilted in the horizontal or vertical planes (Figure 1). Measure a number of lengths (this number is not currently defined but is unlikely to be less than five) with the artefact as close to the Tracker as possible. Repeat the test two further times to give three sets of measurements in all. Repeat the measurements using the second face of the instrument (only necessary if the manufacturer's instrument specifies measurements can be made in both faces).

Figure 1. Initial position of the artifact with respect the tracker

(b) Position the artefact as far away from the tracker as possible and within the instruments specified distance measuring capability (say between 10 to 15 metres away) then repeat the procedure described in 1 to obtain further sets of measurements (Figure 2).

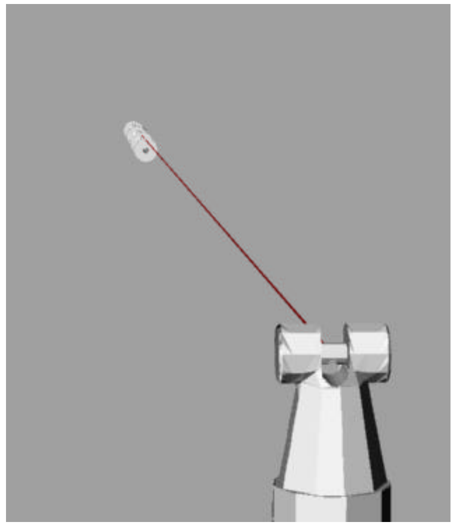

Figure 2. Measurement of the artifact at the furthest practical distance.

If the instrument has an absolute distance measuring system, repeat the measurements again using this system.

(c) Position the tracker midway between the two above positions and repeat the measurement procedure described in 2 using both the interferometer and absolute distance measurement (Figure 3).

These three sets of measurements can be used to assess the performance of the laser interferometry independently from the angle sensors.

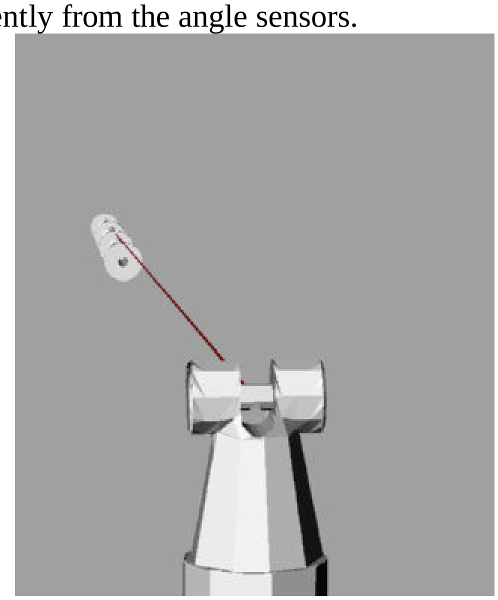

Figure 3. Final length measurement test at the intermediate distance

Verification of horizontal encoder performance

(a) Set-up the artefact as illustrated in Figure 4 so that the angle that will be made between the tracker and the two end points of the artefact is approximately 90 degrees. Ensure that the artifact is parallel to the Tracker's horizontal axis. Measure the specified number of lengths repeated three times for both faces.

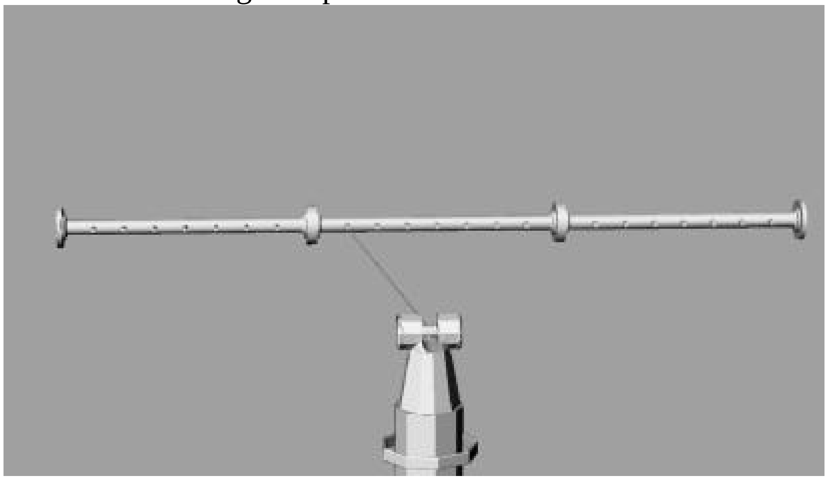

Figure 4. Horizontal angle encoder verification set up

(b) Move the artefact and repeat the measurements in each of the three further quadrants to the other side of the tracker (or rotate the body of the tracker through 90 degrees).

These measurements give information largely independent of the vertical angle encoder and the interferometer.

Verification of the bird-bath distance

If the manufacturer specifies a bird-bath error then the following procedure should be used. Place the artifact as close to the tracker as is practically possible (approximately 150-300 mm - see Figure 5), in the same plane as the horizontal encoders and at the same height as the mirror. Measure the distances between measurement points near the two extremities of the artifact (Loser & Kyle, 2000) - it is not necessary to measure points that are closer than approximately 0.75 metres.

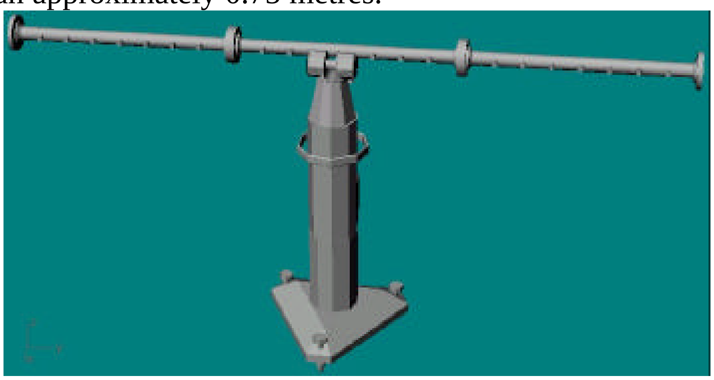

Figure 5. Measurement of the bird bath distance

Verification of the vertical encoder performance

(a) Set up the artefact so that it is standing vertical and close enough to the tracker to ensure that the highest points is near to the maximum elevation of the tracker of the highest elevation the user wishes to verify the tracker performance for (Figure 6). Measure the specified number lengths repeated three times. Repeat for the two face measurements.

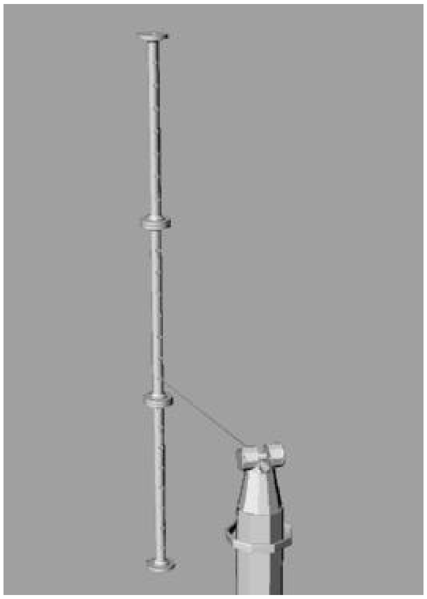

Figure 6. Verification of vertical encoder performance

(b) Place the artefact at the furthest distance the tracker must be verified for and repeat the measurements described in (a)

These measurements allow the performance of the vertical angle encoder to be established without significant dependence on the other sensors.

Verification of combined vertical and horizontal encoder performance

(a) Set-up the artefact close to the Tracker so that opposite ends of the artefact are equi-distant from the Tracker, and at an angle of approximately 45 degrees in the vertical plane, and measure the probe locations the specified number of times.

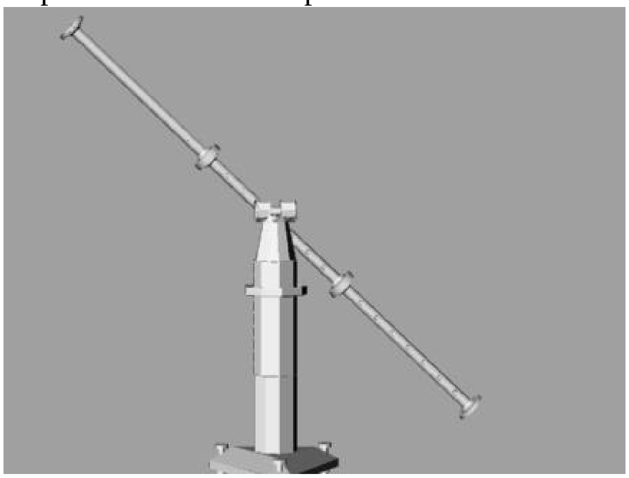

Figure 7. Combined angle measurements position 1.

(c) Rotate the artefact 90 degrees in the vertical plane so that the end nearest the floor is now up in the air at 45 degrees (Figure 8) and repeat the measurements.

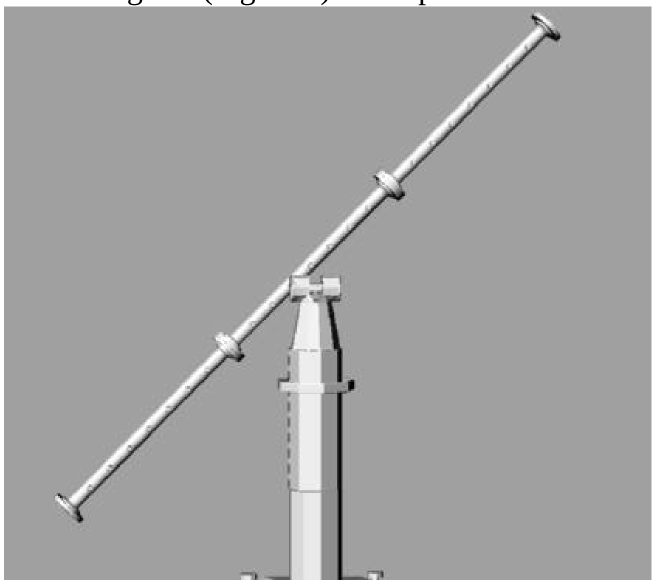

Figure 8. Combined angle measurements position 2.

Verification of the combined angle and distance performance

(a) Set-up the artefact at a compound angle to the Tracker and measure the lengths as for combined angles procedure (Figure 9). Select another compound angle and repeat (Figure 10).

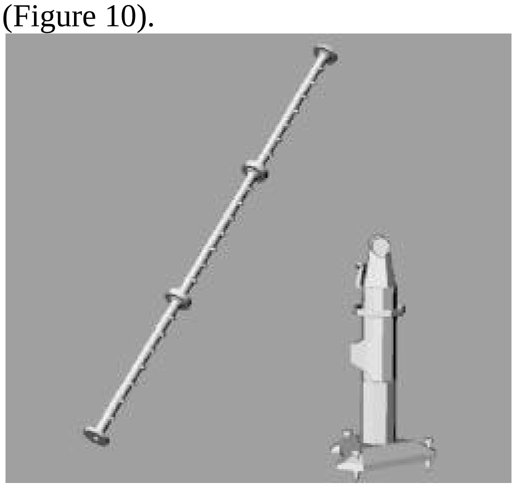

Figure 9. Compound angle position 1.

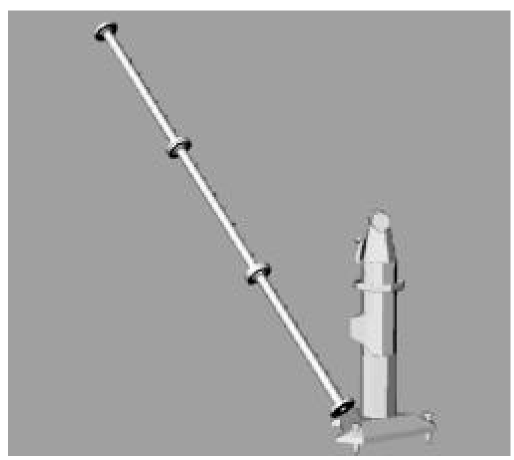

Figure 10. Compound angle position 2.

These additional measurements aim to detect any interaction in error behaviour between the sensors. The complete set of measurements make it is possible to analyse the behaviour of the laser tracker. The measurements fully test the capabilities of all the sensors and allow the performance to be checked against the specification provided by the manufacturer in terms of the statistical model for the sensors. In fact, the information gathered from the verification test can be used to update the manufacturer's specification and help predict the performance of the tracker on other tasks based on a history of actual measurements.

5. Preliminary results

Experiments with laser trackers using the NPL large reference length artifact are used to illustrate the general approach. The results obtained are preliminary and the lessons learned are being fed into revised procedures and new tests. In these experiments, the artefact was not used in its traceable mode which normally requires the use of a relatively heavy collimator to check the straightness of the artifact. Instead a series of measurements of the artefact were taken using the laser tracker at close range and the results were combined and taken as a temporary repository of the reference lengths. This approach was sufficient for development purposes.

5.1. Verification of the performance of the interferometer against its specification

The procedure discussed in section 4 was used to assess the performance of the interferometer. The error map for the configuration is illustrated in Figure 11.

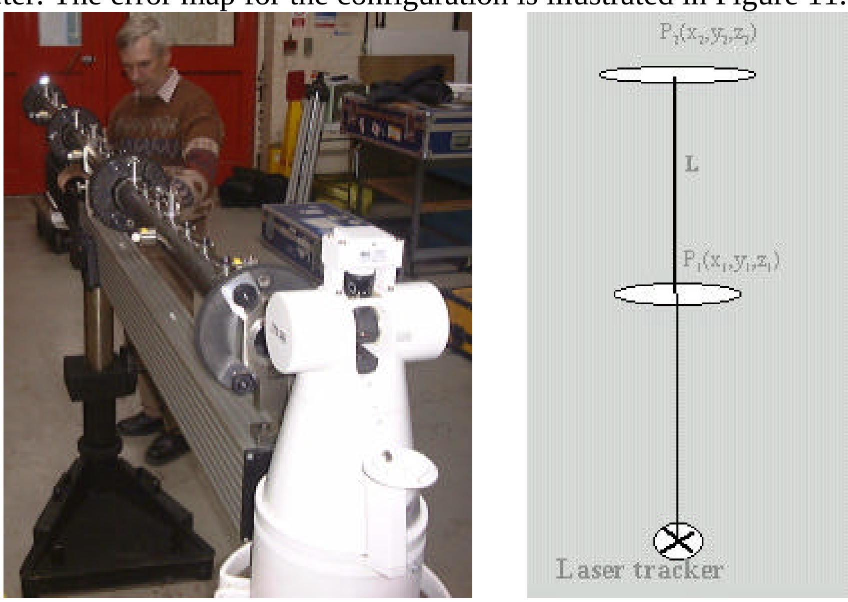

Figure 11. Practical set up for procedure and error distribution for the laser tracker and artifact during interferometer assessment

The length artefact was placed at three locations, i.e., far (average distance = 17.5 metres), middle (average distance = 9 metres) and near (average distance = 1.9 metres), with respect to the laser tracker. Nine points on the artefact were carefully measured by the laser tracker (each of them six times, three on face one and three on face two). Thirty six measured lengths between those points were then compared with the calibrated lengths of the artefact. At each location 216 lengths were compared. The absolute differences between the measured lengths and the calibrated lengths were considered laser tracker's length measurement errors. The measurement errors and the predicted errors for 9 meter distance are plotted in Figure 12. The predicted errors were in general greater than 30 microns and the measured errors less than 20 microns. The length measurement errors of the laser tracker were all less than the predicted errors. This means that the performance of the interferometer was within manufacture's specification.

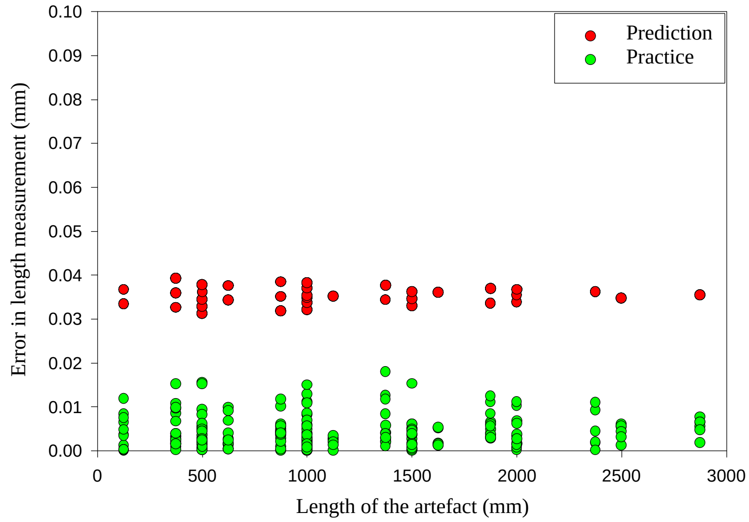

Figure 12. Comparison between the predicted accuracy and that obtained in practice for the interferometer at a distace of 9 metres

5.2. Verification of the performance of the horizontal angle encoders against the manufacturers specification

To verify the horizontal angle measurement performance the artefact was placed horizontally. The horizontal encoders were assessed according to the procedure discussed in section 4 using the same reference artifact. The time, temperature, and pressure differences between tests were small enough not be considered an issue.

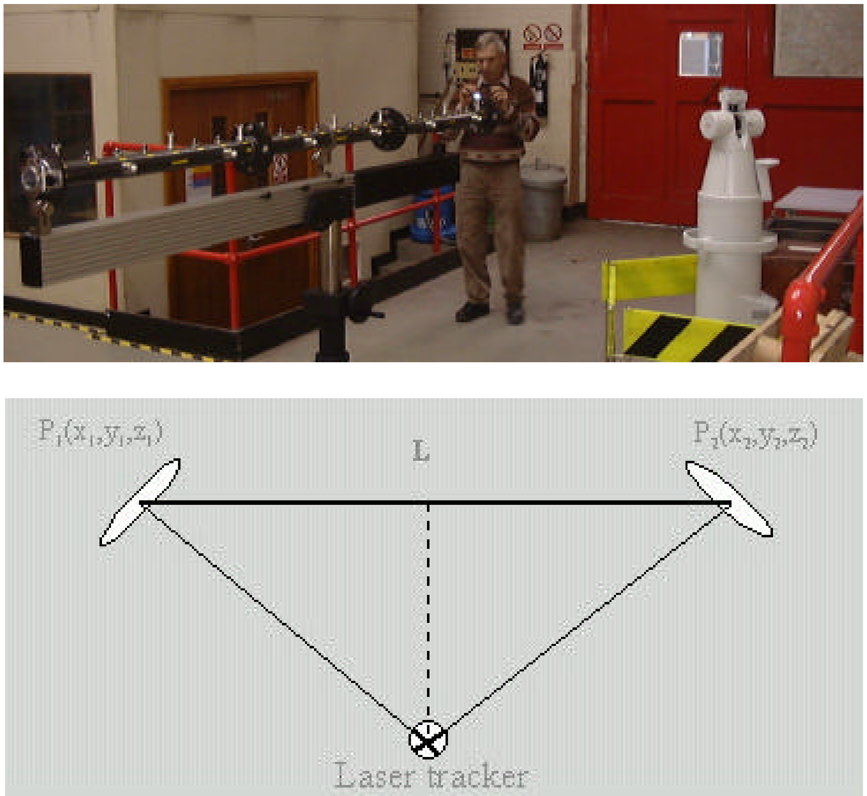

Figure 13. Practical set up of the verification procedure for horizontal encoder assessment and expected error distribution for angle measurements

Each of the nine points on the artefact were measured six times (three for each face) with the artefact placed about 2 meters away from the tracker. The body of the tracker was rotated through three 90 degrees to complete the three further quadrants. A total of 864 lengths were measured. The absolute differences between the measured lengths and the calibrated lengths (the length measurement errors of the laser tracker) were compared with the predicted errors. The artefact was then placed to a further distance (9 meters) away from the laser tracker. Only one quadrant was tested. The results of 216 length measurements were plotted in Figure 14. The results showed that the length measurement errors of the laser tracker were all less than the predicted errors. This means that the performance of the horizontal encoder was within the specification.

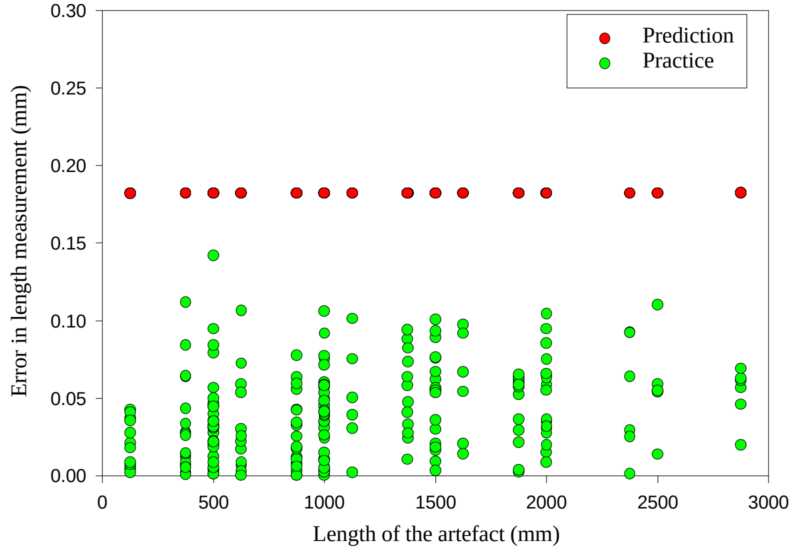

Figure 14. Comparison between the predicted accuracy and that obtained in practice for the angle encoders at 9 metres

5.3 .3 Results of the verification experiment

In both cases illustrated the capability of the measurement system was verified to be within specification.

6. Conclusions

A large volume measurement system verification methodology has been created. The method has been tested on laser tracker and photogrammetry systems and the results obtained suggest that the method is suitable for purpose. It is practical, taking less than one day to perform and is based upon a traceable physical artifact. There is sufficient redundancy and variation in the measurements to characterize the measurement system. Software has been written that makes the procedure relatively simple for the end user but a rigorous analysis is performed. Further work to define the number of measurements and refined the specification for suitable length artifacts are among the items that will addressed in the ongoing work. Other measurement systems such as such as theodolites and portable arm CMM’s have also been investigated but further work is required to complete the corresponding procedures.

It is hoped that the research and development work conducted will form a solid basis for the implementation of verification procedures for large volume measurement systems in industry and eventually contribute to new standards set by the appropriate bodies. For instance, a preferred rewrite of the ISO 10360-2 scheme would define the generic methodology to be applied for example, modeling of the measurement system, use of a measured lengths, development of a verification procedure for each different system designed to estimate parameters with maximum efficiency, testing and refinement of the procedures, application of the procedure using software. A specific section would then be dedicated to each measuring system such as the conventional CMM, portable arm, laser tracker, photogrammetry, theodolite, etc.

7. Acknowledgements

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