

Design and uncertainty of an opto-mechanical device for checking CMM touch trigger probes

P.A. Cauchick Miguel

*CT - UNIMEP, Rodovia Santa Bárbara-Iracemápolis, Km 1, 13450-000
Sta Bárbara d'Oeste, Brazil - Tel. +55 19 463 2311, Fax +55 19 455 1361*

Tim G. King

*Man. & Mech. Eng., The University of Birmingham, Birmingham B15 2TT,
UK - Tel. +44 121 414 4266, Fax + 44 121 414 6800 (e.mail t.king@bham.ac.uk)*

Abstract

This paper presents aspects of design of a test apparatus for checking touch trigger probes. It describes the probe test rig whose main objective is to check the probe repeatability and pre-travel variation (lobing effects). The results indicate that such a verification has been achieved with the additional advantage of testing the probe independent of the CMM error sources. The paper details the design characteristics of such a system for which the combined uncertainty is computed. Finally, it concludes that its accuracy is good enough for CMM probe performance verification.

Keywords

CMM probe, probe performance verification, probe test rig, touch trigger probe

1 INTRODUCTION

Undoubtedly the probe system is one of the key elements of CMMs (Coordinate Measuring Machines), especially touch trigger probes. These are the most common probe-type applied (approximately 90% of the market). In addition to the appropriateness of using touch trigger probes for CMM measurements, there are applications other than those of coordinate metrology. For example, a touch trigger probe can be incorporated into a machine tool for in-process control. One of such application has been to fit a probe system to a machining centre to establish the centre line on a crank seal bore, as employed in the Jaguar plant at Radford, near Coventry, UK. However, the probe performance is a major factor contributing to CMM measurement uncertainty. Inaccuracies in the probe mechanism will affect CMM measurement results. Therefore, the nature of probe-related errors and uncertainty must be quantified (e.g. see Butler, 1990; Miguel, 1996). Many tests have been devised to established the magnitude of possible error contributed by the probe. None of them, however, consider a test independent of the machine so that errors in the probe are usually superimposed on those of the CMM. This paper covers the performance verification of the probe system, particularly touch trigger probes, applying the concept of a new probe test apparatus, including analysis of the main error sources of such a system.

2 TOUCH TRIGGER PROBE VERIFICATION USING A TEST RIG

Traditional probe testing methods involving artefacts, whilst useful, are not always indicative of the probe performance as a completely independent functional unit. Hence, a probe test rig has been developed for checking kinematic-resistive probes, presented in the following sections.

Probe Test Rig Design

The required hardware of the probe test rig consists of a motorised traversing table coupled with a laser interferometer which enables the laser to be employed as the table measuring scale. A gauge block, is then fixed on the traversing table providing a reference surface for triggering the probe. Figure 1 illustrates the schematic arrangement of the probe test rig including all components.

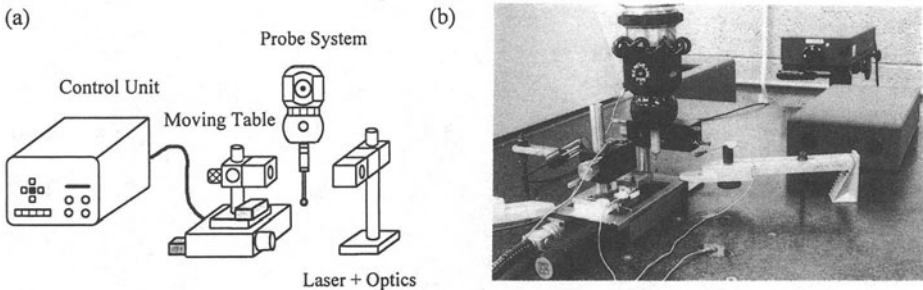


Figure 1 Probe Test Rig Arrangement (a) and Actual CMM Set up (b).

The components of the proposed test rig can be basically divided into; a translational stage with controller, a laser interferometer, and a probe interface. A commercial motorised stage with a travel range of 50 mm was used as the moving element for triggering the probe. The design of the carriage utilises linear ball bearings with twin track bearings disposed laterally on each side on the carriage slides. It has a dc servo motor to propel the carriage along the table base. The table is interfaced to a controller providing forward and reverse traversing movement, with automatic origin search.

The test procedure consisted of measuring the distance from the table origin to the point where the probe was triggered. The table was moved forward until the gauge block touched and triggered the probe. The laser display reading was taken and the table was moved back to its home position. The probe head was then rotated through a 7.5° interval and the stage moved forward to trigger the probe again. This cycle was repeated until the probe head has been rotated by 360° of indexing angle ($\pm 180^\circ$) making a total of 48 points. The collected data were used to calculate both the standard deviation (repeatability) and the pre-travel variation over 360° of the head rotation.

The laser interferometer is linked to the probe system to provide a signal for reading the laser display, as illustrated in Figure 1. When the surface of the gauge block touches the probe ball tip, the signal from the probe is sent to the laser computer via a PCMCIA card. The system employed the laser 'TPin' facility. It allows data to be captured by the laser system upon receipt of a trigger signal initiated from the machine under test. This is provided from a relay within the CMM controller, via the probe interface module. Data capture may be triggered either asynchronously or synchronously. In both modes, the trigger signal must be a clean debounced TTL, CMOS, or SSR signal. The mode used was TPin synchronous data capture which provides a higher speed hardware trigger facility greatly reducing the delay between the leading edge of the TPin pulse and the instant that the laser reading is recorded.

The motorised probe head is used for rotating the TP2 probe to successive angular positions. In order to retain the function of the head while the probe is triggered, it is necessary to link the probe interface unit to the probe head controller (housed in the CMM cabinet). The interface unit used is capable of automatic recognition and interfacing the probe system. Figure 2 shows all necessary links between the laser interferometer, probe head controller, and probe interface unit. The main advantage of this configuration is the good compatibility between all components since they are produced by the same manufacturer.

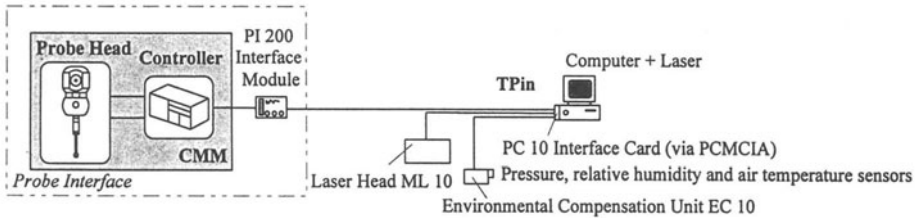


Figure 2 Interface between the CMM and Laser System.

Experimental Set up of the Test Rig on the CMM

The set up of the experiment comprises the alignment of the stage, retroreflector, laser head, and the gauge block (see Figure 1b). First, the table was set up on the CMM table by aligning it parallel to the X-axis using two reference points measured by the CMM. Second, the reflector was also aligned with the table and consequently with the X-axis direction of travel. Third, the laser head was properly adjusted in relation to the table carriage (to which the retroreflector was fixed). Then, the linear interferometer was placed in a fixed position between the laser head and the moving retroreflector. After fine adjustments, a maximum laser strength signal was obtained. The translational table could then be moved incrementally over the whole traverse range while readings were taken by the laser. Although the experiment has been set up in a controlled environment (temp.: $20^{\circ}\text{C} \pm 1^{\circ}\text{C}$ and humidity: $50\% \pm 5\%$), air and material temperature sensors were placed at the test area. Pressure and relative humidity were also taken from the environment unit in order to automatically compensate variation in the refractive index of the air. Finally, the gauge block was aligned, using the CMM, perpendicular to the table's traverse movement. In all cases, the alignment was considered good enough when the CMM coordinates of the reference points were the same.

3 ERROR SOURCES IN THE PROBE TEST RIG

There are several sources of errors associated with the proposed test rig. Some of them are related to the motorised table itself and others to the laser system. These error sources have been described, in detail, in previous publications (Renishaw, 1989; Steinmetz, 1990; Miguel, 1996) and are summarised in the following sections.

Table Repeatability and Angular Errors

It is clear that, irrespective of the motion mechanism employed, the proposed system depends upon adequate repeatability and low rotational errors to perform effectively. It is therefore necessary that these errors are measured to determine whether the translational table is suitable for this particular application. Such verification has been presented and discussed elsewhere (Miguel, 1996). The angular motions associated with the moving stage are pitch and yaw angular errors. In terms of yaw, it can be assumed that the centre of rotation is in the lead-screw. If the gauge block (in fact, the

spatial position of the centre of the probe ball tip) is maintained aligned with the screw centre line, the yaw errors will be null, or negligible. Investigation on the characteristics through the traverse range revealed a region of constant rate of change for pitch errors (a large interval between 15 and 30 mm from the datum). This interval could be the best for using the table to check the probe system. However, small intervals around 20, 25 and 35 mm seem to have a smaller spread. Assuming the centre of pitch rotation in the centre line of the screw, it is possible to calculate the variation in the table traversing movement for those intervals. The minimum spread of pitch angular error was 1.9 arc-seconds (position at 20 mm). Since the distance from the screw centre line to the probe ball centre is measured as 26.85 mm, the variation in table traversing position due to the errors in the pitch direction will be 0.25 μm (in the position 25 and 35, the error will be 0.35 μm and 0.45 μm , respectively). Therefore, the position of 20 mm was considered the best one for positioning the table when triggering the probe. In fact, the maximum standard deviation for three runs was 0.58 arc-seconds which yields a variation in the traversing table position of just 0.08 μm . The previous analysis has been made to check the influence of pitch and yaw on the gauge block position when touching the probe ball tip. Actually, pitch error is relevant to the test while yaw is not (see next section). Furthermore, there is another parameter which is affected by these angular motions. This is the Abbé offset (or Abbé error), described below.

Abbé Error

Abbé error occurs when the measuring point of interest (in this case the centre of the stylus tip) is displaced from the actual measuring scale location (the position of the laser beam, which is a line through the apex of the cube-corner reflector and parallel to the beam direction). For this error to be avoided, the measurement system must be placed co-axially with the line in which the displacement is to be measured. However, this is not possible on the test rig because the probe system must be shifted from the laser beam path. Abbé error can be represented as $d \times \tan\beta$, where d is the vertical or horizontal offset distance between the laser beam and the centre of the ball tip. The angle β is the variation caused by angular motion of the carriage of the table. It should be noted that yaw affects horizontal Abbé error while pitch affects vertical Abbé error. There is no Abbé sensitivity to roll angular motion. The pitch and yaw errors were found to be 1.9 and 1.4 seconds of arc for pitch and yaw at the chosen table test position (i.e. the best interval, identified in the last section, to be used for testing the probe). The horizontal Abbé offset was not taken into account; it can be considered negligible due to the fact that the gauge block is positioned on the screw centre line. The Abbé vertical offset (due to pitch) was reduced by mounting the reflector as low as possible, i.e. as close as possible to the gauge block top surface. The Abbé vertical distance was measured as being 20 mm. The variation in angular movement for the vertical plane resulted in an error of 0.18 μm .

Atmospheric Conditions

As relatively well-known that the interferometric measurement accuracy is directly determined by how accurately the ambient conditions are known and their stability during the test. The laser wavelength is a function of the refractive index of the ambient atmosphere in which it operates. During linear measurements variations in the refractive index of the air can lead to significant measurement error. The refractive index is dependent upon the temperature, pressure, humidity and chemical composition of the ambient atmosphere through which the beams travels. Therefore, in order to obtain proper results, the laser readings must be corrected for any change in the wavelength of the measurement beam. Errors in the laser wavelength can be reduced by applying either manual or automatic compensation using Edlén's equation (Edlén, 1966) for the refractive index of air under standard conditions of temperature and pressure. This equation is accurate to approximately 0.1 ppm (ANSI/ASME, 1995). This form of equation also assumes atmospheric air with the normal

mixture of gases. Atmospheres that deviate significantly, particularly in regard to CO₂, can lead to measurable errors. If this situation is suspected, appropriate corrections should be applied. However, previous study conducted by Mainsah (1994) indicated that there was little reason to suppose that the concentration of CO₂ was high enough to significantly affect the accuracy to which the measurements were made. These errors can be minimised to less than ± 1.1 ppm by using the laser's environmental compensation unit in automatic mode, providing the environment remains stable during the course of measurement. The Centre for Metrology the CMM resides in a room with controlled conditions of temperature and relative humidity. However, the temperature variation measured over a period of 2 hours was 0.31°C; and over a longer period (7 hours) was 0.79°C.

Laser Wavelength

The laser source of any interferometric system has some type of frequency stabilisation to maintain wavelength accuracy and repeatability. The laser system used in the experiments was a frequency-stabilised He-Ne laser operating at a nominal wavelength of 633 nm. The wavelength stability gives a theoretical accuracy of linear measurement of ± 0.1 μm per metre measured, or ± 0.025 μm with compensation for refractive index changes in air (Downs, 1991).

Deadpath Error

This is an error associated with changes in the environmental conditions during the course of a measurement. The deadpath error (ϵ_{DP}) is related to the distance between the two optical elements, when the system is datummed (Figure 3). This occurs due to an uncompensated length of the laser beam and arises when atmospheric conditions surrounding the laser beam change while a measurement is being taken, thereby causing alteration in the refractive index of the air and hence in the wavelength of the laser beam. Deadpath error is not a function of the measurement length but of the distance DP (see Figure 3). It is a systematic error which is constant for a given system set up.

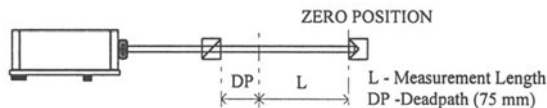


Figure 3 Optical Configuration with Deadpath.

The deadpath error can be expressed by the dead path distance multiplied by the variation in the environmental factor (change in the wavelength compensation) during the measurement time (Steinmetz, 1991). The environmental factor (EF) is the inverse of the refractive index (or λ_A/λ_V , where λ_A is the wavelength in air and λ_V is specified as the wavelength in vacuum). In order to minimise this, the stationary and moving optics were mounted as close as possible following recommendations provided by Downs (1991). He also recommended that whilst this error is inevitable if proper alignment is carried out, its magnitude is usually small enough that detailed quantification is unnecessary. Nevertheless this error was quantified for the probe tests and it was found to be 0.05 μm , when the EF was recorded a few times during 1.5 hours of test.

Material Thermal Expansion

Another factor which could affect the probe test results is the thermal expansion of the table carriage and other CMM components, e.g. the motorised probe head, through the heating generated by their motors. Temperature changes introduce further error sources which can be relevant since solids expand when heated. In order to verify the effects of temperature, sensors were placed at different locations in the traversing table, gauge block, reflector, and CMM surface table. The

temperature variation is particularly unwanted in the gauge block as it could expand during the tests. Considering a uni-directional thermal expansion in the gauge block (towards the probe ball tip), the temperature gradient can lead to an increase in its length up to 0.42µm for a 50.8 mm gauge block (rate of about 1.4°C/h). It was also possible to observe a temperature gradient even in the reflector fixed to the mounting post (0.33°C/h). Therefore, precautions had to be taken in order to minimise this effect. Two materials were tested to isolating the base plate (where the gauge block and the reflector were mounted) from the table carriage. The first material was a layer of polystyrene, well compressed by the clamping system. The second one was a layer of Tuccite™, which is a material used in the assembly of lathes, which is considered good in isolating temperature effects from the motors to the guideways. The temperature increases due to heat transfer from the drive motor can be seen in Figure 4. The results show a great deal of thermal isolation was achieved with both materials when compared with the un-isolated case, since the rate of heating is much reduced. However, the layer of polystyrene achieved a better result compared with the Tuccite™ material (rate of 0.58°C/h and 1.13°C/h, respectively). Therefore, the expansion of the gauge block, using polystyrene, would be reduced to 0.17 µm. However, it was possible to reduce the length of the gauge block to 20 mm yielding an expansion of 0.06 µm.

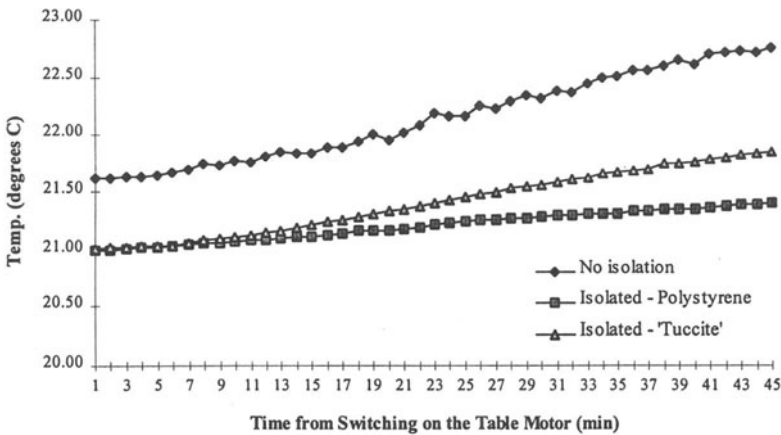


Figure 4 Temperature Variation in the Gauge Block after Isolation.

Cosine Error

Misalignment of the measuring axis (laser beam) with the axis of movement (traversing table) results in a difference between the measured distance and the actual distance travelled, called cosine error (ϵ_c). It is called cosine error because its magnitude is proportional to the cosine of the angle of misalignment. The resulting measurement error is then a function of the distance measured by the interferometer. Therefore, the cosine error can be represented as indicated in Figure 5.

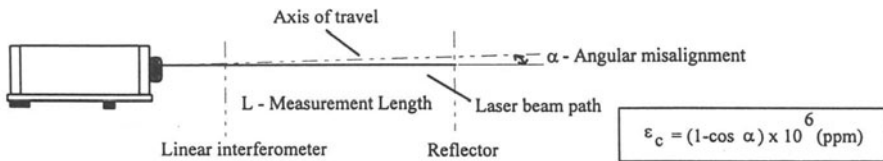


Figure 5 Cosine Error.

The cosine error can be eliminated by orienting the laser beam parallel to the actual axis of travel. However this is not entirely possible and there always will be some misalignment. By following proper alignment procedures, cosine error can be minimised. This was achieved in this experiment by taking some precautions with regard to such a laser beam alignment. Firstly, the reflector was aligned with the axis of travel by probing two reference points in its lateral surface using the CMM until the coordinate (in Y direction) showed the same values for both reference points. Secondly, due care was taken when aligning the laser beam making sure that the reflected beam was in the centre of the laser output aperture (using the provided target) over the full range of the table. Finally, the signal level on the laser display was also used to reduced this error. This was done by fine tuning the alignment to achieve a constant and maximum strength reading over the whole table traversing range resulting in an effective beam alignment. Downs (1991) stated that, with the aid of a position sensitive quadrant detector system, it is possible to align the optics such that the cosine error can be reduced to $0.0015 \mu\text{m}/150 \text{ mm}$. However, such a system was not available for this work. The cosine error has been investigated by Mainsah (1994) and it has been shown that it is practicable under normal laboratory conditions to reduce the error to well under $0.1 \mu\text{m}/50 \text{ mm}$.

Other Error Sources

Additional error sources are the electronics error and optics non-linearity. The electronics error stems from the method used to extend basic optional measurement resolution in an interferometer system. The basic resolution of an interferometer is $1/2 \lambda$ (where λ is the laser wavelength) when using a cube-corner reflector and can be electronic or optically extended beyond $1/2 \lambda$. The interpolation factor in the laser interferometer used is 256 which, combined with the double path of normal linear displacement optics, gives a resolution of $\lambda/512$ which is 1.24 nm. The electronics error equals measurement resolution. The optics non linearity is the ability of an interferometer optical element to perfectly separate the two laser beam components in vertical and horizontal polarisations (Steinmetz, 1991). The non-linearity affects all interferometer systems whether they are single or two frequency. The specifications of these error sources were not available from the laser manufacturer. However, Hewlett Packard provides them for its laser systems. Owing the fact that there are no significant differences between the optics for both systems (Steinmetz, 1991), the values recommended by HP were used for calculating the combined uncertainty.

4 PROBE TEST RIG ERROR ANALYSIS

The results of the analysis of the total error budget associated with the probe test rig (the combined uncertainty). The combined uncertainty (U_c) can be thought of as representing the measuring uncertainty resulting from combining all known sources of uncertainty in a root sum of squares (RSS) manner (by assigning them a variance). It resulted in an $U_c = 0.25 \mu\text{m}$. This approach is based on the CIPM method, according to the ISO Guide to the Expression of Uncertainty in Measurement (1993). Further improvement in the uncertainty model will be done as a future work.

5 CONCLUSIONS

The achievements using the probe test apparatus described in this paper have shown that it serves the purpose of checking the main error sources in the probe system within an accuracy which can be considered satisfactory for this stage of development. Nevertheless, the limitations to the accuracy attainable to the test rig have been quantified including a number sources of uncertainty for this particular application. The error source which contributes most to its uncertainty was the Abbé offset, but this occurred due to physical constraints of the system. The U_c value has been calculated

for the worst possible situation but it would be expected to be smaller than the 0.25 μm . The full results from probe tests will be reported in a future paper. It is believed that the main advantage of the probe test rig is to support CMM users when inspecting their probes either in their acceptance or during their useful life as an important aspect of industrial production.

6 ACKNOWLEDGEMENTS

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7 REFERENCES

- ANSI/ASME B89.4.1 (1995). Methods for Performance Evaluation of Coordinate Measuring Machines. The American Society for Mechanical Engineering, New York, December Draft.
- Butler, C. (1991) An Investigation into the Performance of Probes on Coordinate Measuring Machines. *Industrial Metrology*, **2**(1), 59-70.
- Downs, M.J. (1991) Optical Metrology: The Precision Measurement of Displacement Using Optical Interferometry, in *From Instrumentation to Nanotechnology* (ed. by J.W. Gardner and H.T. Hingle), Gordon and Breach Science Publishers, 213-226, USA.
- Edlén, B. (1966) The Refractive Index of Air. *Metrologia*, **2**(1), 71-80.
- Mainhah, E. (1994) Investigation of Pre-characterisation Aspects of Three-dimensional Microtopography. PhD Thesis, The University of Birmingham, UK.
- Miguel, P.A.C. (1996) CMM Performance Verification, Considerations for a Virtual Artefact Approach. PhD Thesis, The University of Birmingham, UK.
- Renishaw Interferometer System User Handbook (1989). Renishaw Transducer Systems Ltd.
- Steinmetz, C.R. (1990) Performance Evaluation of Laser Displacement Interferometry on a Precision Coordinate Measuring Machine. *Industrial Metrology*, **1**(3), 165-191.

8 BIOGRAPHY

Paulo A. Cauchick Miguel

Paulo Miguel graduated in Industrial Engineering at the Universidade Metodista de Piracicaba (UNIMEP) in 1986. He then worked as a manufacturing engineer for Allied Automotive and Varga companies until 1990 when he became a lecturer in the Centro de Tecnologia at the UNIMEP. In October 1993 he moved to the University of Birmingham, UK, to join the Mechatronics group in the School of Man. & Mech. Eng. His research activities include quality and metrology developments, and engineering education. Paulo Miguel completed his PhD in December 1996.

Tim G. King

Professor Tim King BSc (Eng), MDes RCA, PhD, FRSA is Professor of Mechanical Engineering at the University of Birmingham where he heads the Mechatronics Research Group in the School of Man. & Mech. Eng. His current research includes development of ultra-high speed piezoelectric actuators, piezoelectric motors, calibration techniques for surface metrology and CMM applications, and microprocessor and DSP based systems for computer-visual inspection and controls of deformable patterned materials. He is author of more than 90 journal and conference papers.