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Evaluation of automated flexible gauge performance using experimental designs

M. Papananias[a], S. Fletcher[a], A. P. Longstaff[a], A. Mengot[b], K. Jonas[b], A. B. Forbes[c]

[a]*Centre for Precision Technologies, University of Huddersfield, UK*
[b]*Renishaw plc, UK*
[c]*National Physical Laboratory, UK*

Abstract

An essential part of assessing whether a measurement or gauging system meets its intended purpose is to estimate the measurement uncertainties. This paper employs the design of experiments (DOE) approach to implement a practical analysis of measurement uncertainty of Renishaw Equator automated flexible gauge. The factors of interest are measurement strategy, part location, and environmental effects. The experimental results show the ability of the versatile gauge to effectively meet its measurement capability in both discrete-point probing and scanning measuring modes within its whole measuring volume and, in particular, at high scanning speeds and under workshop conditions.

1 Introduction

Quality assurance at low cost hints at a tight interaction between machining and inspection in order to reduce scrap levels and production costs while increasing part throughput. Identifying defective parts immediately after they have been manufactured is of special importance because it enables effective in-process feedback from process control on the shop floor, reduction of inspection scrap and bottlenecks, since defective parts can be excluded immediately without the need for further processing, etc. [1]. Therefore, over the last few years, it has been the driving force for many research projects.

Coordinate measuring systems (CMSs) such as coordinate measuring machines (CMMs) have been used for decades in traditional manufacturing industry to ensure that the size and form of a part conform to design specifications [2]. Although CMMs are considered as accurate measuring systems, most are unable to maintain their measurement capability on the shop floor, and therefore, they are usually employed in quality control rooms typically having environmental temperature control systems set to maintain 20°C. In addition, the measurement results they normally provide are subject to a large number of influencing factors including both random and systematic effects [3]. In particular, factors that could affect the accuracy of CMM measurements are: 1) environmental effects; 2) machine repeatability; 3) machine thermal errors; 4) machine geometry errors; 5) scale errors; 6) probing system errors; 7) machine dynamics; 8) vibrations; 9) measurement strategy; 10) measurement part; 11) fixturing variability; and 12) software errors. Therefore, the evaluation of uncertainty associated with CMM measurement is a very complex task though many different approaches have been developed to cope with it [3, 4].

Other types of CMMs such as articulated arm coordinate measuring machines (AACMMs) are manually-operated CMMs consisting of a number of articulated arms equipped with angular encoders [5, 6]. However, AACMMs have much lower measuring accuracy than conventional CMMs and require highly skilled operators to assure confidence on the measurement results and, even so, dimensional inspection with AACMMs provides high measurement uncertainties. Another common approach for manual dimensional inspection in traditional manufacturing includes various gauges such as height gauges, dial gauges, calipers, micrometers, etc. Nevertheless, this approach tend to be inflexible, it can be time consuming and costly due to required calibration of each hard gauge, it results in high measurement uncertainties, and as with AACMMs, the repeatability, reproducibility, and part throughput depend on operators.

The demand of modern manufacturing industry for faster and more accurate automated dimensional inspection on the shop floor has led to new developments in adjustable variable gauging [7]. In particular, Renishaw has developed a novel comparative gauging system called Equator that employs the comparator principle through software to account for the influence of systematic effects associated with the CMS [8]. The Renishaw Equator automated comparator can cope with temperature changes on the shop floor by re-zeroing the gauging system through the principle of mastering managed with the built-in sensor and software configuration. Furthermore, the Equator machine is based on an easily scaleable and adaptable parallel kinematic structure in order to overcome the dynamic performance barrier of Cartesian CMMs at high measurement speeds [9], since inspection cycle times are important to maintain part throughput at desired levels. Therefore, the main uncertainty contributors associated with comparative coordinate measurement can be considered to be: 1) calibrated master part; 2) machine repeatability; 3) fixturing variability; 4) measurement strategy; 5) software errors; 6) environmental effects, but regular re-mastering accounts for reducing these effects; and 7) part temperature and form deviations, but multiple master files can also be used to reduce these effects.

This research applies a couple of full factorial designs [10] to investigate the performance of the Equator gauging system in discrete-point probing and scanning measuring modes within its whole measuring volume in workshop environments. The remainder of the paper is organised as follows: Section 2 introduces the Equator gauging system; Section 3 presents the first experimental design concerning the inspection of a clutch plate with touch-trigger probing (TTP), in nine different locations under both temperature controlled and uncontrolled environments; Section 4 presents the second experimental design concerning the inspection of a RESR ring with scanning, in five different locations under workshop conditions; Section 5 deals with the analysis of the comparator measurement uncertainty; and finally, concluding remarks are given in Section 6.

2 Renishaw Equator flexible gauge

The comparative gauging system used for this experimental study is the Renishaw Equator 300. The Equator gauging system comprises the Equator gauging machine, the Equator controller, and the Renishaw SP25 3-axis analogue scanning probe as shown in Figure 1. The Equator machine is composed of three linear drive struts separated by an angle of 120° with respect to each other. Each drive strut is equipped with a linear encoder and is mounted on the Hooke’s joint on the fixed top casting. The probe (movement) platform of the Equator is constrained by a parallel kinematic constraint mechanism so that it can remain parallel to the fixture plate or fixed base casting. Therefore, the assumptions generally made to simplify the kinematic analysis of delta robots are largely avoided.

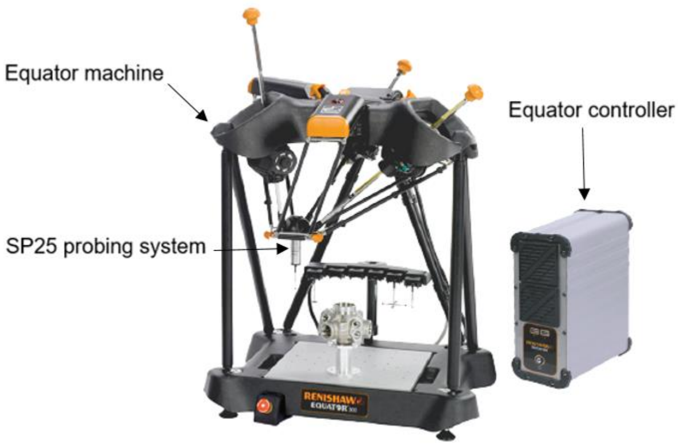

Figure 1: Equator 300 gauging system

The Equator comparator has a cylindrical working envelope with the dimensions ø300 mm x 150 mm. It is equipped with a Renishaw 3-axis SP25 analogue scanning probe to enable both scanning and TTP. The Equator gauging machine is powered directly from its controller, which contains all the software required to run the system. Therefore, an additional computer is not employed when operating the Equator and thus, eliminating the chance of incompatibility or unpredictable performance arising from the wide variation of computer architectures.

The Equator uses part programs written using the internationally recognised dimensional measuring interface standard (DMIS) language. In order to generate a master data set, a master part is measured using the measurement routine produced to measure each test part. Each test data set is then compared to the master data set to determine the actual size of the test part and assess its conformance to the engineering drawing. The two main compare methods employed by the Equator gauge are the Golden Compare and the CMM Compare. The Golden Compare method uses a reference part, called master, to calibrate the Equator, while the CMM Compare method employs a production part that has been previously calibrated by an accurate CMS such as a CMM. This work employs the Equator gauge operating in Golden Compare.

3 Comparative coordinate measurement based on discrete probing

A full factorial design was employed using discrete probing to investigate the effect of part location and ambient temperature on comparator measurement uncertainty. The part used is a clutch plate with an internal nominal diameter of 77 mm and an external one of 98.4 mm. The stylus used is a typical 21 mm long stylus with stainless steel stem and a 2 mm diameter ruby ball. A general overview of the experimental setup is shown in Figure 2.

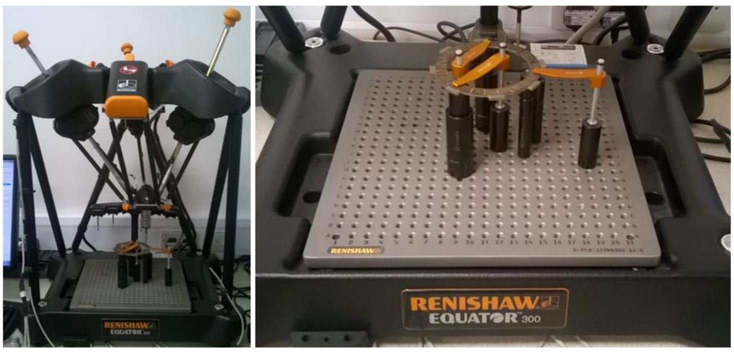

Figure 2: Test setup on Equator gauge for the clutch plate

The part was placed in nine different locations within the Equator's measuring volume in order to cover its whole working volume. The measurements were performed at 20-22°C and 27-29°C and, in both cases, the part had been thermally stabilized at each temperature before mastering. Temperature readings were recorded during the experiment using additional temperature sensors to record the temperature variation of the environment. The measurands were the internal and external diameters. For both diameters seven points were selected to be taken. The measurement of the clutch plate was followed immediately after mastering and repeated twenty times without re-mastering and without moving the part. Therefore, in total, 720 diameters were determined; 360 internal diameters and 360 external diameters. Figure 3 depicts the nine different locations where the part was placed.

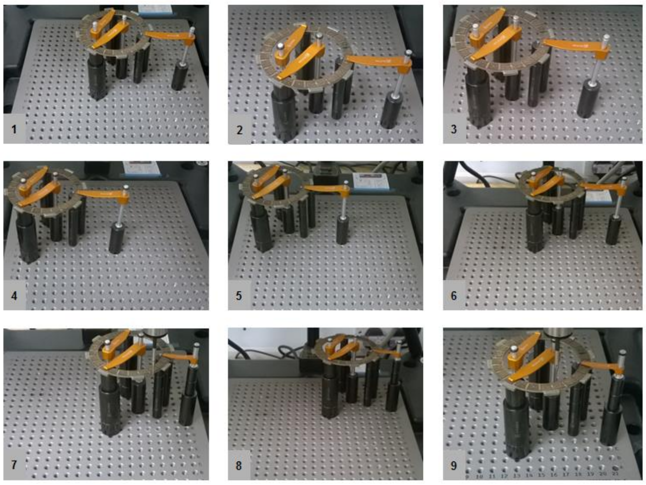

Figure 3: Clutch plate locations

4 Comparative coordinate measurement based on scanning

Another full factorial design was employed to investigate the effect of (A) scanning speed, (B) sampling point density, and (C) part location on comparator measurement uncertainty when scanning. The part used for this study is a RESR ring. This part has thirteen circular features; six small holes with a nominal diameter of 3.6 mm, six medium holes with a nominal diameter of 6 mm, and a large circle with a nominal diameter of 80 mm. The measurands of interest in this case study were the diameter of one of the small holes (the hole at 0° according to the coordinate frame of reference) and the internal diameter of the large circle. The stylus used for this experimental design is the same (21×2) with that used for the previous study concerning TTP.

In scanning CMMs, a major limitation at higher scanning speeds is the high measurement uncertainties due to dynamic influences [9]. Therefore, this study sought to evaluate the uncertainties associated with automated flexible gauging at high scanning speeds. Hence, three levels were used for the scanning speed. The first level corresponds to 5 mm/s for the small hole and to 25 mm/s for the large circle. Levels 2 and 3 are, respectively, the double and quadruple values of the scanning speeds used for level 1. So, they are 10 mm/s and 50 mm/s for level 2 and 20 mm/s and 100 mm/s for level 3. Regarding the factor of sampling point density, two levels were used; level 1 corresponds to a sampling distance (the distance between sample points on the scan path, in the current units) of 0.5 and level 2 to a sampling distance of 0.1. The RESR ring locations are shown in Figure 4.

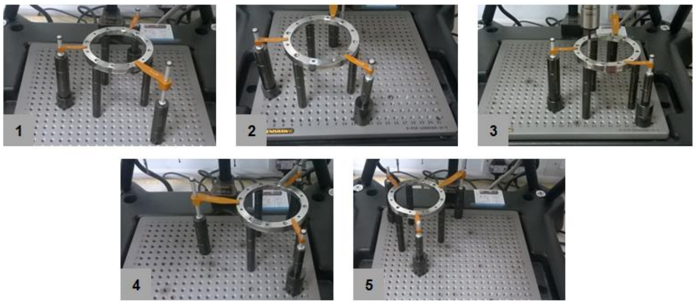

Figure 4: RESR ring locations

As with the previous experimental design presented in Section 3, twenty repeated measurements were performed immediately after mastering on the same part. Therefore, in total, 600 diameters were determined for each feature. Also, temperature readings were recorded during the experiment, and the part had been thermally stabilized at 28-29°C before mastering.

5 Comparator measurement uncertainty evaluation

For each set of twenty repeated measurements, the expanded comparator measurement uncertainty was determined following the uncertainty evaluation methodology given in ISO 15530-3-2011 [11] as follows:

$$U = ku(y) + |b| \tag{1}$$

where k is the coverage factor, b is the systematic error, calculated by the difference between the sample mean value and the expected or calibrated value thus, $b = \bar{y} - y_{cal}$, and $u(y)$ is the standard uncertainty of the mean value of the measurements and given as:

$$u(y) = \frac{\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(y_i - \bar{y})^2}}{\sqrt{n}} \tag{2}$$

In addition, a normality test was performed for each measurand to determine whether the measurement data followed a normal distribution, and all judged to be satisfactory. Therefore, Figures 5 and 6 show the main effects plots produced using Minitab for the expanded measurement uncertainties *U* of the internal and external diameters of clutch plate, for k=2 and a confidence level of 95%, when the Equator is used in TTP mode.

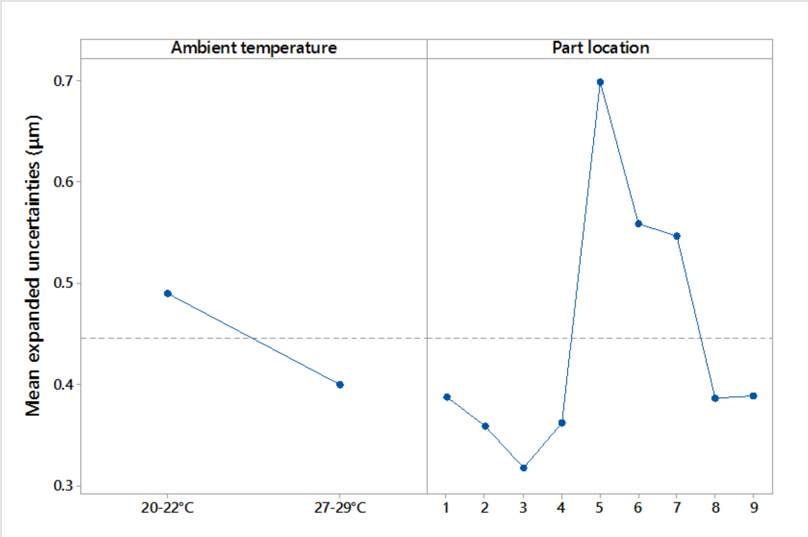

Figure 5: Main effects plots for the uncertainties of internal diameter

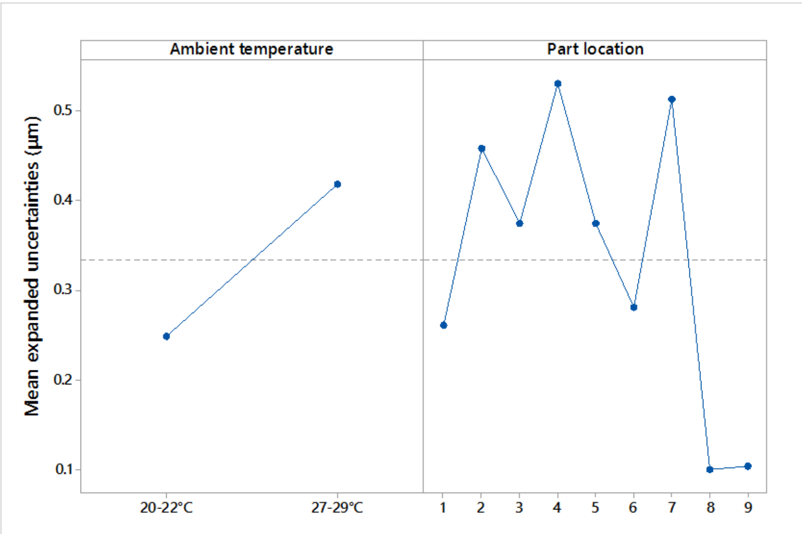

Figure 6: Main effects plots for the uncertainties of external diameter

The results in Figures 5 and 6 show that the comparator measurement uncertainty is less than 1 µm within the whole measuring volume of the versatile gauge in TTP mode and under both temperature controlled and shop floor conditions. Similarly, Figures 7 and 8 show the main effects plots for the expanded measurement uncertainties *U* of the diameters of features of interest for k=2 and a confidence level of 95% when the versatile gauge is used in scanning mode.

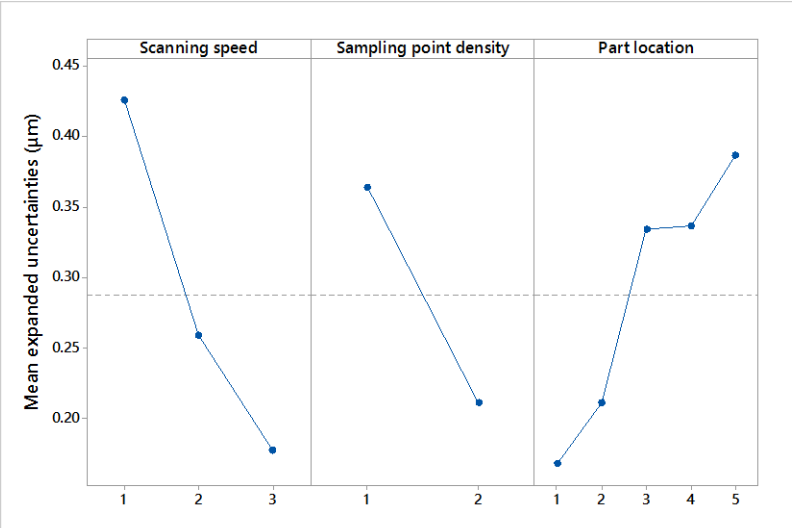

Figure 7: Main effects plots for the uncertainties of diameter of large circle

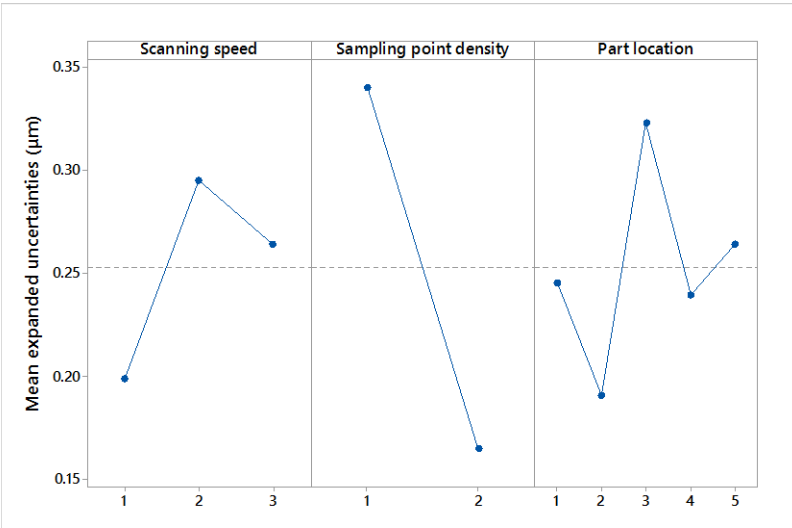

Figure 8: Main effects plots for the uncertainties of diameter of small hole

The results in Figures 7 and 8 show that: the machine dynamics does not limit measurement accuracy at higher scanning speeds; the higher the sampling point density, the lower the comparator measurement uncertainty; and, the comparator measurement uncertainty is less than 0.5 µm within the whole measuring volume of the versatile gauge in scanning mode and under shop floor conditions (28-29°C). Table 1 shows the results obtained by the ANOVA procedure based on ordinary least squares (OLS) regression for 95% confidence level using Minitab.

Table 1: ANOVA results

Measurands	p-values						R^2
	A	B	C	A*B	A*C	B*C	
Diameter of large circle	0.073	0.079	0.382	0.033	0.811	0.562	81.14%
Diameter of small hole	0.507	0.029	0.788	0.881	0.510	0.778	71.51%

Based on the ANOVA results, the statistically significant factors and their interactions for 95% confidence level (p-values < 0.05) are: the interaction of scanning speed and sampling point density for the diameter of large circle where the model explains 81.14% of the variance and the sampling point density for the diameter of small hole where the model explains 71.51% of the variance.

6 Conclusions

The modern view of quality control requires highly repeatable automated inspection systems, capable of being integrated into the manufacturing process, for automatic process feedback to ensure high product quality and low rejection rates. Following the current requirements of manufacturing industry, and considering the fact that one of the most important factors affecting the performance of a coordinate measuring machine (CMM) in a machining environment is the ambient temperature, Renishaw has patented a flexible gauging comparator, called Equator. The Renishaw Equator is a versatile gauge that employs the comparator principle through software to account for the influence of systematic effects associated with the measurement system.

In this work, two experimental designs have been employed to perform a practical analysis of uncertainty of measurement of the Equator gauging system, in discrete-point probing and scanning measuring modes (especially at high scanning speeds), within its whole measuring volume and under workshop conditions. The experimental results have illustrated the advantages that can be achieved in terms of inspection speed and repeatability with shop floor process control based on automated flexible gauging. Therefore, dimensional inspection on the shop floor with automated flexible gauges based on parallel kinematic structure is proposed as an optimal solution to fill the gap between CMM measurement and traditional manual gauging.

Further work is required to quantify the benefits that can be achieved in fully automated applications and to develop best practice and supporting documentary standards.

Acknowledgements

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