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Uncertainty evaluation associated with versatile automated gauging influenced by process variations through design of experiments approach

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ABSTRACT

Recent advances in versatile automated gauging have enabled accurate geometric tolerance assessment on the shop floor. This paper is concerned with the uncertainty evaluation associated with comparative coordinate measurement using the design of experiments (DOE) approach. It employs the Renishaw Equator which is a software-driven comparative gauge based on the traditional comparison of production parts to a reference master part. The fixturing requirement of each production part to the master part is approximately ±1 mm for a comparison process with an uncertainty of ±2 μm. Therefore, a number of experimental designs are applied with the main focus on the influence of part misalignment from rotation between master and measure coordinate frames on the comparator measurement uncertainty. Other factors considered include measurement mode mainly in scanning and touch-trigger probing (TTP) and alignment procedure used to establish the coordinate reference frame (CRF) with respect to the number of contact points used for each geometric feature measured. The measurement uncertainty analysis of the comparator technique used by the Equator gauge commences with a simple measurement task using a gauge block to evaluate the three-dimensional (3D) uncertainty of length comparative coordinate measurement influenced by an offset by tilt in one direction (two-dimensional angular misalignment). Then, a specific manufactured measurement object is employed so that the comparator measurement uncertainty can be assessed for numerous measurement tasks within a satisfactory range of the working volume of the versatile gauge. Furthermore, in the second case study, different types of part misalignment including both 2D and 3D angular misalignments are applied. The time required for managing the re-mastering process is also examined. A task specific uncertainty evaluation is completed using DOE. Also, investigating the effects of process variations that might be experienced by such a device in workshop environments. It is shown that the comparator measurement uncertainties obtained by all the experiments agree with system features under specified conditions. It is also demonstrated that when the specified conditions are exceeded, the comparator measurement uncertainty is associated with the measurement task, the measurement strategy used, the feature size, and the magnitude and direction of offset angles in relation to the reference axes of the machine. In particular, departures from the specified part fixturing requirement of Equator have a more significant effect on the uncertainty of length measurement in comparator mode and a less significant effect on the diameter measurement uncertainty for the specific Equator and test conditions.

1. Introduction

The traditional approach to dimensional inspection on the shop floor is based on hard gauging because coordinate measuring machines (CMMs) require temperature controlled rooms to adequately meet their measurement capability. Certainly there are major differences between manual inspection and automated

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inspection [1]. Briefly speaking, CMMs are accurate measuring instruments and potentially more versatile and flexible than custom hard gauges. However, they are very costly and require environmental conditions that are unlikely to be met in a shop floor environment. Consequently, this approach proves unsuitable for effective feedback to the production loop. Also, the time required for the inspection cycle can often be longer than the manufacturing cycle itself due to the need to transfer the manufactured parts to the quality control room after the machining process is finished and thermally stabilize them. Dedicated gauging is time consuming and costly, since traceable calibration is required for each hard gauge, and, the repeatability and reproducibility depend on operators. Also, hard gauges require a level of re-engineering when the design of the parts to be measured changes and thus potentially increasing production bottlenecks.

Other types of coordinate measuring systems (CMSs) used in manufacturing include articulated arm coordinate measuring machines (AACMMs), which are manual CMMs. AACMMs are portable and flexible instruments, but they are much less accurate than CMMs [2,3]. As with CMMs, they are also thermally sensitive, though they have a much simpler construction. In addition, unlike automated inspection systems, the manual control of AACMMs adds a non-predictable error source, the operator, and thus producing worse values of repeatability and reproducibility [4].

Although CMMs are one of the most powerful and versatile metrological instruments, the determination of measurement uncertainty of CMMs is not straightforward due to the various influencing factors including both random and systematic effects [5]. However, the influence of systematic effects associated with the CMM can be much reduced in comparator mode in which a machine having high repeatability is required [6,7]. In particular, the substitution method [8], where the CMM is used as a comparator, generally decreases the measurement uncertainty and is used extensively, especially for measurement tasks with high accuracy requirements. In fact, the comparison between the calibrated value of the working standard and the indication of the CMM shows the systematic deviations of the CMM that can be subsequently used to correct the measurement results of production parts. Therefore, the problem of performing an uncertainty budget for comparator measurements is much simpler than CMM measurements [9].

To bridge the gap between CMM measurement and custom hard gauging, automated flexible gauges based on a parallel kinematic structure to ensure high repeatability at fast operating speeds have been recently adopted for process control on the shop floor. Such flexible gauges employ the comparator principle through software to account for the influence of systematic effects associated with the measurement system [6,7]. So, an automated flexible gauge provides all of the automation features of tactile CMMs, but it does so without actually requiring temperature controlled conditions due to the comparator principle. The advantages of the comparator method employed by a CMS are further discussed in Section 3.

The purpose of this work is to study the performance of automated flexible gauge in a shop floor environment using experimental designs. The remainder of the paper is organised as follows. Section 2 presents the background of research concerned with uncertainty evaluation associated with coordinate measurement through experimental designs. Section 3 describes the comparator method for dimensional measurement. Section 4 introduces the automated comparative gauging using a simple measurement task. The fundamental parameter of misalignment is explained and examined along with other important parameters. Section 5 presents the second case study consisted of preliminary and main experiments utilizing a specific manufactured measurement object. Full factorial designs are applied in both case studies to investigate all the possible interactions of the factors through analysis of variance (ANOVA) methods. The measurement results obtained from both case studies are analysed using Minitab. Finally, concluding remarks are given in Section 6.

2. Background

A large number of research works in the domain of coordinate metrology has been conducted to quantify the measurement accuracy of CMSs such as CMMs and increase it by improvements in hardware, software, and general measurement strategy. In order to ensure that the measurements are accurate, the calibration of the CMM needs to be traceable to the international system of units (SI), in particular, to the international standard of length with known measurement uncertainty [10]. However, CMMs are multi-purpose measuring systems and therefore demonstrating traceability to national standards and, ultimately, to the international standard is not straightforward. Therefore, the only practical way of ensuring that the CMM measurements are accurate is to provide measurement-task-specific traceability statements [10,11]. As a matter of fact, the uncertainty associated with the measurement of a specific feature through a specific measurement strategy is usually referred to as task specific uncertainty. An excellent review for uncertainty sources and methodologies developed to model and assess task specific uncertainty for coordinate measurements is provided by Wilhelm et al. [5]. These authors divided uncertainties associated with CMSs into five main categories: hardware, workpiece, extrinsic factors, sampling strategy, and fitting and evaluation algorithms. Weckenmann and Knauer [12] focused on the last two factors and showed that the way the CMM operator defines the measurement strategy has a strong influence on the CMM measurement uncertainty.

An efficient way to plan and conduct experiments in manufacturing metrology is the method of design of experiments (DOE), which assesses the sensitivity of the measurand to various factors that comprise the measurement process. There is a number of DOE techniques such as factorial designs, response surface designs, Taguchi orthogonal array designs, etc. [13,14]. In manufacturing industry, the most commonly used approach includes factorial designs [15]. Factorial designs fall under two main categories: full factorial designs and fractional factorial designs. Fractional factorial designs are an alternative to full factorial designs when the number of factors is large because they use fewer runs than the full factorial designs. However, only the full factorial designs include all possible combinations of every level of every factor so that all the possible interactions among the factors can be examined. Response surface designs are usually used to refine models after the important factors have been determined using factorial designs [16]. Taguchi orthogonal array design is a type of general fractional factorial design and therefore interactions between the factors are normally not taken into consideration [17,18].

In the reviewed literature, numerous studies have been reported in evaluating the uncertainty associated with coordinate measurement through the DOE method. For example, Barini et al. [19] described a study associated with point-by-point sampling of complex surfaces using a tactile CMM. They carried out a completely randomized full factorial experiment with four factors at two levels each and concluded that the analysis of factorial experiments can help determine the statistically important factors. Similar conclusions, but for length type features of ball bar gauges, were made by Piratelli-Filho and Giacomo [20] who applied a 3^2 factorial design for carrying out a performance test using a ball bar gauge and for investigating CMM errors associated with orientation and length in the work volume. Feng et al. [21] employed a sequential experimentation approach through fractional factorial designs for the measurement uncertainty evaluation of the location of a hole measured by a CMM equipped with a Renishaw TP2 touch-