# The application of uncertainty evaluating software for the utilisation of machine tool systems for final inspection

P. Saunders[1, 2], M. Verma[1, 2, 3], N. Orchard[1], P. Maropoulos[2]
[1]*Manufacturing Technology, Rolls-Royce plc, UK*
[2]*Department of Mechanical Engineering, University of Bath, UK*
[3]*Machine Tool Technologies Ltd., UK*

## Abstract

As machine tools continue to become increasingly repeatable and accurate, high-precision manufacturers may be tempted to consider how they might utilise machine tools as measurement systems. In this paper, we have explored this paradigm by attempting to repurpose state-of-the-art coordinate measuring machine Uncertainty Evaluating Software (UES) for a machine tool application. We performed live measurements on all the systems in question. Our findings have highlighted some gaps with UES when applied to machine tools, and we have attempted to identify the sources of variation which have led to discrepancies. Implications of this research include requirements to evolve the algorithms within the UES if it is to be adapted for on-machine measurement, improve the robustness of the input parameters, and most importantly, clarify expectations.

## 1 Introduction

Machining systems exist in order to produce features in accordance to a specified design. Similarly, the purpose of a measurement system is to validate the output of such machining systems whilst referring to this same specification. Good practice in metrology is to ensure that measurement systems are independent of machining systems in order to guarantee validity. However, as machine tools become increasingly capable and stable, some users of these machines may wish to test this principle of independence. Indeed, it is becoming a routine matter to employ measurement probes for in-process checks whilst machining [1]. By extension, one might wonder if for some tasks, a machine tool system is truly capable of taking on the additional role of final inspection.

In the sections that follow, a theoretical comparison is made of the main differences between measuring on a machine tool, and measuring on a single purpose measurement system such as a Coordinate Measuring Machine (CMM). With reference to a case study, a report is made on an attempt to repurpose CMM-based Uncertainty Evaluation Software (UES) for measurement on a machine tool. Through a discussion of the results, the authors reflect on the validity of using UES to simulate measurement on machine tools, and highlight research challenges and potential applications.

## 2 Theory

### 2.1 Uncertainty evaluation for CMMs

The state of the art in evaluating measurement uncertainty on CMMs is to use Monte-Carlo based simulation, employing software that is referred to in the standards as Uncertainty Evaluating Software (UES) [2]. Simulation has potential to save considerable time when validating and optimising measurement processes. From a user perspective, UES systems can be broadly classified according to how input data is collected. The first type is closely integrated with a specific CMM; a comprehensive model of the CMM is developed, typically by the CMM manufacturer when commissioning the software. During measurement, further inputs may be acquired, for example through a special probe qualification routine and gathering temperature data. The second type was developed to allow for the case when less complete information is available. For example, one may only have machine performance data in the form of a calibration report. For this second type of UES, a wider range may be associated with the input. Although the result may be less certain, less effort is required to gather the input values. As in any simulation, there will always be factors that UES does not consider, and consequently it can only provide an estimate for part of the total measurement uncertainty [2]. The challenge for users is to understand the capabilities and limits of their chosen UES for a given situation, so that they can direct their efforts in gathering appropriate inputs.

UES was conceived, and is actively recommended, by metrology standards organisations [3]. It has been shown to be valid in practice [4]. Due to the versatility of CMMs, it would be presumptuous to assert that UES is the right solution for every scenario; indeed, the majority of papers relating to UES reviewed by the authors exercised caution in generalising results (e.g. [5]). Nonetheless, many applications have been found, and the approach is regarded as state-of-the-art [6].

For this study, an established commercial off-the-shelf UES system was selected. It can be regarded as a hybrid of the two types described above, since a range of options are available as to the degree of detail that needs to be entered into the system [7].

## 2.2 Uncertainty evaluation for machine tools

Whilst methods for determining measuring performance when using a machine tool for measurement are described in the standards [8], the authors have been unable to find a UES system specifically designed for this environment. There are evidently physical differences between machine tools, which are designed to withstand harsh environments, and CMMs, which are typically housed in more luxurious conditions. Yet when considering them both as measurement devices they are not especially dissimilar. When not cutting, it can be argued that a machine tool will have the same error sources as any CMM. Differences are likely to be found, however, in the relative magnitude and dynamics of those errors. For this study, the authors have used a taxonomy introduced by Wilhelm *et al.* [9], who grouped CMM uncertainty sources into five categories: hardware, workpiece, sampling strategy, algorithms, and extrinsic factors.

Table 1 lists uncertainty contributors in the hardware category, against each of which comments are made as to the likely suitability of the UES to model a typical 3-axis milling machine. With only a few exceptions that are discussed at the end of this section, the other error categories were considered to be substantially similar in this context; this is because UES has been specifically designed to deal with the errors that arise through the interaction of the workpiece, sampling strategy, and algorithms [5,7], and the authors cannot conceive of a reason why these should differ significantly for a machine tool when in a measuring mode. The remaining category covers extrinsic factors, such as cleanliness or variation in fixturing procedures; these are rarely included in any simulation software.

Table 1: Suitability of utilising CMM UES for a 3-axis milling machine

| **Uncertainty contributor** | **Suitability** | **Comments** |
|---|---|---|
| Hardware parametrics | High | The UES is capable of producing full parametric models for both 3-axis CMMs and machine tools. It can be argued that spindle alignment errors are not covered, though it is contended that this is a minor issue because typically spindles are locked whilst probing, and such spindle errors can be accounted for via probe calibration. |
| Probing system | Acceptable | UES will use the same algorithms irrespective of the measurement system. It is found, however, that some probing systems are not covered by the UES. Since probing technology for both CMMs and machine tools is continuously evolving, approximations of capability will need to be made. E.g. scanning probes are best modelled by approximating to a touch probe. |
| Dynamics (machine and probe) | Acceptable | Reversal errors, comprising hysteresis and backlash, are well-recognised problems with machine tools. UES may not be designed to take account of dynamic errors since they affect CMMs less. Such errors can be managed through volumetric error compensation, backlash compensation, and the use of intelligent probing |

| **Uncertainty contributor** | **Suitability** | **Comments** |
|---|---|---|
| | | strategies. Inertial effects are also not covered by the UES, though it has been suggested that this can be mitigated through using robust probing systems, appropriate feed rates, and probing strategies. |
| Temperature | Questionable | UES is able to model the cooling or warming of parts once machining has finished, though it does not have robust algorithms that distinguish between the external and internal heat sources present on a machine tool, especially immediately after machining. Advanced machine tool builders will claim that through utilising thermally stable materials, considerate design principles, and smart cooling systems, thermal stability can be achieved to +/-1 °C whilst machining [10]. |
| Vibration | Acceptable | Despite UES not explicitly covering vibration, it can be partially modelled as a random error component. Where machine tools do experience vibration from a greater number of sources, this error is found to be rarely greater than 1μm on high-precision machines when not cutting. |

Based on the analysis in Table 1, it can be concluded that there is potential in using UES as a predictor for measurement uncertainty on machine tools. This is based on the assumption that the asset in question has been correctly calibrated, has verified probing systems, and is dynamically stable. It is believed that all other hardware contributors can be mitigated through intelligent probing strategies and process monitoring.

Referring back to the other categories in Wilhem *et al.*'s list, three further sources of uncertainty were identified that should be considered. The first relates to the validity of the software algorithms used by the multitude of CNC controllers and how they are validated; the second concerns sources of contamination existing within the machine tool, such as swarf, coolant, and dust; the third pertains to air turbulence within the machine volume. For example, machine tools have air purge systems which are not present on CMMs.

## 3 Experimental method and results

The experiment was split into two stages. In stage one, the selected UES was validated against a known workpiece in a CMM environment; in stage two, the same workpiece, and similar measurement process, was taken to a machine tool.

### 3.1 Stage 1: Validation of UES for a CMM application

The Zeiss CMM Check® is designed for performing regular overchecks on the accuracy of CMMs. It consists of a set of calibrated artefacts, comprising a ring gauge, cylinder, three spheres, and two length bars. Measurement data were obtained from one production facility, where regular tests are being performed on 3 different CMMs located in the same controlled laboratory. Measurement uncertainty was calculated based on this data by applying the substitution method described in ISO 15530-3 [11]. The focus of the experiment was to be on the size of circular features for pragmatic reasons. It allowed the measurement strategy to be mimicked more closely, made good use of existing data, and kept the experiment concise.

There are a number of options available to describe the cartesian errors in the selected UES. The most detailed method is to enter a full parametric model, based on the measured performance of the CMMs. In this study, the decision was made to use performance data from a recent calibration. This approach was deemed suitable based on previous studies in a similar context [4].

Table 2 shows the results, presented in a format consistent with the examples in ISO 15530-3 [11]. The 3 spheres are excluded for brevity. There were over 30 data points for each CMM. The process was run weekly over a 7 month period.

Table 2: ISO 15530-3 v. UES predictions for ring and cylinder

| | **Ring (nom. 49.9983 mm)** | | | **Cylinder (nom. 50.0015 mm)** | | |
|---|---|---|---|---|---|---|
| | CMM A | CMM B | CMM C | CMM A | CMM B | CMM C |
| $u_{cal}$ | 0.00020 | 0.00020 | 0.00020 | 0.00020 | 0.00020 | 0.00020 |
| $u_p$ | 0.00230 | 0.00176 | 0.00180 | 0.00159 | 0.00199 | 0.00140 |
| b | 0.00231 | -0.00071 | -0.00151 | -0.00281 | -0.00133 | 0.00080 |
| $u_b$ | standard uncertainty of the systematic error - negligible | | | | | |
| $u_w$ | standard uncertainty from the manufacturing process - negligible | | | | | |
| $U_{k=2}$ | 0.0046 | 0.0036 | 0.0036 | 0.0032 | 0.0040 | 0.0028 |
| $U_{k=2} + \| b\|$ | 0.0069 | 0.0043 | 0.0051 | 0.0060 | 0.0053 | 0.0036 |
| $U^{sim}_{k=2}$ | 0.0051 | 0.0060 | 0.0050 | 0.0051 | 0.0059 | 0.0050 |
| $U^{sim}_{k=2}/U_{k=2}$ | 0.74 | 1.41 | 0.97 | 0.85 | 1.1 | 1.38 |
| $sd^{sim}$ | 0.0025 | 0.0028 | 0.0024 | 0.0025 | 0.0028 | 0.0024 |
| $sd^{sim}/sd$ | 1.08 | 1.58 | 1.33 | 1.56 | 1.40 | 1.70 |

| | | |
|---|---|---|
| where | $u_{cal}$ | standard uncertainty of the calibrated workpiece |
| | $u_p$ | standard uncertainty of the measurement procedure |
| | b | systematic error |
| | $U_{k=2}$ | expanded measurement uncertainty from the substitution method |
| | $U^{sim}_{k=2}$ | expanded measurement uncertainty based on UES predictions |
| | sd | standard deviation from the substitution method |
| | $sd^{sim}$ | standard deviation based on UES predictions |

The UES had been expected to overestimate uncertainty in every case; for example, as seen by the values highlighted in Table 2. However, there are instances where UES has underestimated uncertainty when compared to the substitution method (0.74 in the worst case). This is reasonable because extrinsic factors are not included in the simulation (see section 2.2). Furthermore, on examining the standard deviation ratios ($sd^{sim}/sd$), all simulations overestimated as compared to the results from physical testing. This was unsurprising, given the decision to accept ISO 10360-2 performance data, rather than to gather full parametric models. Based on these results, it was concluded that the UES operates sufficiently for the chosen features on this particular artefact. The next step is to model a machine tool within UES to correlate with these results.

## 3.2 Stage 2: Repurposing UES to on-machine probing

The selected machine tool is a vertical milling machine of WYXZT configuration, as depicted in Figure 1. The machine was installed in 2011 and has never been used for continuous production. The machine's working volume is 1 m x 0.5 m x 0.5 m; it is ball-screw driven and equipped with Heidenhain linear glass scales on all axes. A Siemens Sinumerik 840D Shopmill controller is installed, together with a Renishaw Rengage RMP600 touch probe. The OEM claims linear accuracy of 0.005 mm per 300 mm, and +/- 0.002 mm repeatability on all axes. The machine was an ideal candidate for experimentation since:

1. The specification is representative of a machine which one might be tempted to use for measurement, and hence forms a platform to perform simulation upon;
2. The machine is not in production use, and hence does not experience temperature gradients associated with machining, and it is not heavily contaminated;
3. The machine is based within a laboratory, which although not temperature-controlled, is considered thermally stable due to its location in the building and its isolation from other equipment.

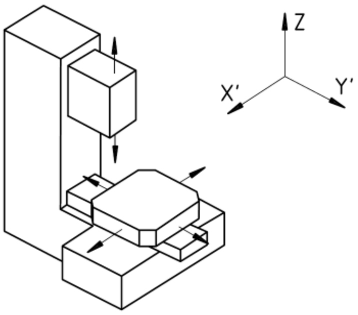

Figure 1: Configuration of 3-axis milling machine (diagram from ISO 10791-2)

In view of the uncertainty contributors identified in section 2.2, the primary sources of discrepancies were dealt with as follows:

1. Calibration data of the machine was acquired prior to probing, based on ISO 230-1 and ISO 230-2 methods; positional errors were re-measured after the experiment so that changes could be observed;
2. The probe was calibrated using industry standard techniques;
3. Probing feed rates would be as per OEM specification;
4. Industry standard probing software (Renishaw Productivity+) was employed to implement the measurement strategy;
5. The temperature was continuously monitored;
6. PTB-validated CMM software was used to post-process the results;
7. Contamination and turbulence was reduced to minimum levels.

Accordingly, the first step was to check the machine was in a suitable condition for experimentation through the use of a Renishaw XL80 laser interferometer system and ball bar. The positional errors and circularity data were deemed to be acceptable. Although the machine could not be regarded as ‘high-precision’, it was repeatable to a standard which could confidently be modelled in the UES.

Next, all 21 geometric errors of the machine tool were assessed, with compensation on, using the laser interferometer. Material temperature sensors were located close to the X-axis scale and on the work surface of the machine; there was no significant discrepancy in temperature over 3 days of testing. Other industry standard techniques (ISO 230-1) were used to measure errors where the laser interferometer could not. Based on these measurements for this ‘representative’ machine, a design of experiments study was carried out with the aid of the UES system. The experiment was 6 factor, 2 level, full factorial, using the settings shown in Table 3. The response was the predicted uncertainty of feature size (at 95% confidence limits), assuming a least-squares best fit.

Table 3: Factors in DOE

| **Factor** | **Low** | **High** |
|---|---|---|
| Probe standard deviation | 2.0 µm | 0.5 µm |
| Temperature range | +/-2.5 °C | +/-0.5 °C |
| Machine repeatability | as measured in lab | 0.5 µm standard deviation |
| Measurement strategy | 4 points (2 rows on cylinder) | 9 points (2 rows on cylinder) |
| Machine accuracy | as measured in lab (poor) position A | as measured in lab (good) position B |
| Feature type | ring | cylinder |

The low settings in Table 3 represent ‘average industrial conditions’, whilst the high settings represent ‘improved industrial conditions’ (borrowing terminology from ISO 230-9). The 64 trials produced a range of uncertainty values, from 1.1 µm when all factors were set high, to 9.0 µm when all factors were set low. This compares with uncertainty estimations of between 5.0 µm and 6.0 µm for the 3 CMMs, for which the UES was shown to be a good predictor of uncertainty. Figure 2 is a Pareto chart, showing these factors and second order interactions. It can be seen that the uncertainty is dominated by the machine repeatability and the probe standard deviation.

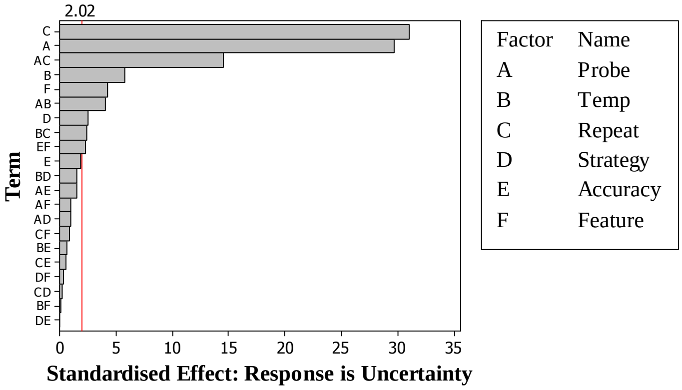

Figure 2: Pareto chart of the standardised effects

In the laboratory, it was not practical to change the dominant contributors of machine repeatability and probe standard deviation; nor could the temperature range be altered. Variable inputs were thus restricted to feature type, measurement strategy, and machine accuracy (by moving the artefact to different positions in the working volume). However, the DOE results suggest that it should have been possible to identify an effect.

1580 measurements were taken in total, through repeating 3 different measurement strategies on the ring and cylinder features 10 times in 2 positions. By isolating those measurements where probing involved movement in just one axis, an average standard deviation was calculated, as shown in Table 4.

| | **Position A** | **Position B** |
|---|---|---|
| X-axis | 9.2 μm | 7.6 μm |
| Y-axis | 11.0 μm | 5.7 μm |
| Z-axis | 0.9 μm | 0.2 μm |

Table 4: Average standard deviation in each axis

The UES had indicated an upper limit of 9.0 μm uncertainty for feature size, whilst Table 4 suggests that this could be completely consumed by one standard deviation of a single point. Suffice to note, that despite efforts to minimise the impact of errors specific to performing the measurements on a machine tool, the authors were unable to demonstrate correlation with UES predictions.

## 4 Discussion

The UES uncertainty predictions correlated well with the uncertainty calculated from physical measurements on the CMMs. UES predictions for the ‘representative’ machine tool in ‘improved’ industrial conditions were approximately 50% greater than they were for the CMMs. However, the results from physical measurements on the machine tool showed significantly higher uncertainty than these predictions. This discrepancy for on-machine probing was unforeseen by the theoretical analysis summarised in Table 2. Furthermore, the calibration data collected indicated that the machine was less repeatable than had been expected based on the manufacturer specification. This too was unexpected, considering that the machine was new and little used. The calibration data also showed significant reversal/backlash error in the machine which could have affected probing because circular features being measured.

In theory, the authors still believe that UES has potential for proven high-precision machines if adequate process control and asset care are enforced. Through this research, key parameters have been identified, and a process has been established which could be replicated swiftly for other machine tools. Bearing in mind the demonstrated capability of UES for CMM applications, there is scope to develop it further so that it can signal inadequacy and/or potential for a machine tool’s capability to measure. However, one still relies on the relevance and traceability of the machine tool’s parametric model.

There are a number of options for creating such a parametric model. Each has its own advantages and disadvantages. One option is to make use of machine tool specifications from the OEM, though this carries risk, as was found in this experiment. A second option is to use an equivalent standard as used for CMM validation [6]. A third option is to measure the machine before probing, though with current technology this can take several days and traceability of the uncertainty of this process would also need to be confirmed, making for a challenging business case in an industrial context. The authors foresee extensive debate continuing regarding the choice of parametric model. Irrespective of model choice, guaranteed on-going equivalence is a pre-requisite.

Reflecting on the attempt to repurpose this particular UES for machine tool application, it was found to be possible to miss-assign input parameters. For example, bi-directional errors are not currently catered for in the model. It is therefore critical that a standard approach is developed and unified for describing inputs to UES systems, as without this there is potential to confound errors [6]. For instance, an error connected with the probing system could be attributed to the machine. Expected future improvements to UES generally would encompass higher levels of standardisation of terminology and interfaces, increased data automation, and integration with other manufacturing systems.

Following on from this study, the authors believe that it would be valuable to repeat the experiments on a variety of high-precision machines. More features, measurands, and different sizes should be investigated. The contribution that UES could have on industry from a manufacturing perspective is substantial.

## 5 Concluding remarks

The CMM is one of the most widely deployed measurement devices for high-precision manufacturers. CMMs are versatile, robust, and cost-effective; consequently, they have become critical resources in many organisations. Today high-precision machine tools are designed and built with similar attributes as CMMs and with comparable accuracy. Therefore, it is understandable that machine tool users pursue ways of reinventing their equipment as CMMs.

Metrologists will always require the uncertainty of any measurement device to be quantified with respect to its given application. Simulation software is the state-of-the-art approach for evaluating task-specific uncertainty on CMMs. For an inventive individual who wishes to use their machine tool as a CMM, a logical step to satisfy metrologists may be to repurpose CMM-based Uncertainty Evaluating Software (UES).

This case study was a tentative step towards exploring the capability of UES when applied to on-machine probing. UES was found to have potential in this domain, although there are fundamental issues that need to be resolved, including: choice of input model; the source and input of data; ensuring ongoing asset capability; process control; and expectation management. Therefore, the authors cannot yet justify its use in a typical industrial setting. As an emergent finding from this research, it was learnt that caution must be exercised when using OEM specification data of a machine tool as an input parameter to UES.

Theory suggests that one might be able to apply UES under certain 'improved' industrial conditions for high-precision machines. This might only apply for certain tolerances and features. Further work should be carried out to identify the system boundaries. This process can be achieved through the establishment of a knowledge base comprising machine tool specialists, metrologists, and simulation software developers.

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