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The role of extrinsic factors in industrial task-specific uncertainty

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ABSTRACT

The measurement of large components using portable measuring equipment is important to many industries, including ship-building and aerospace. Portable measuring instruments – such as laser trackers, laser radar, indoor GPS, and other systems – are used to obtain measurement data for process control, assembly alignment, or geometric conformance decisions. Traditional uncertainty estimations often focus on the measuring instrument and its performance as a primary contributor to the overall uncertainty for specific measurands. The research reported here focuses on the uncertainty contributors that are due to extrinsic effects such as part deformation due to gravitational loads and thermal distortion of the workpiece, where the uncertainty contribution from the instrument is considered insignificant in comparison.

1. Introduction

Modern day large-scale industrial measurements are becoming more difficult to perform with newer, more sophisticated design requirements. With new design requirements, tolerance specifications are becoming tighter thus requiring high-accuracy measurement instruments. Measurements of large-scale components using Cartesian Coordinate Measuring Machines (CMMs) tend to be limited given the size requirements of the instrument needed; therefore, a need for alternative measurement capabilities must be addressed. Portable measurement instruments – such as laser trackers – are efficient alternatives as the components can be measured in-situ. In many cases, the slight degradation in measurement accuracy due to the measuring environment is small when compared to the influence of extrinsic effects on the component. These effects are often either uncorrected or ignored completely, which in turn affects the validity of the measurement results. Furthermore, uncorrected extrinsic effects result in an unknown bias in the measurement results, which increases the likelihood of non-conformance to design specifications. This paper reports on investigations into how extrinsic effects, namely deformation due to gravitational loads and thermal distortion of the workpiece, can be modeled when considering only two-dimensional geometries initially. Furthermore, how the effect from imperfect modeling contributes to the measurement uncertainty associated with the measurement of the workpiece geometries under investigation.

2. Current standards and extrinsic effects

The *Guide to the expression of Uncertainty in Measurement* (GUM) [1] suggests that all known systematic effects be corrected prior to estimating the uncertainty of the measurand of interest. In essence, the GUM principles are task-specific but require a full mathematical model of the measurand, an imposing challenge for all but the simplest of measurands. Task-specific uncertainty has been defined as the measurement uncertainty associated with the measurement of a specific feature using a specific measurement plan [2]. While it might be argued that all measurements are task-specific, this makes a more useful label due to the flexibility of CMMs. A CMM can measure many different types of features, and the uncertainty associated with each measurand may be quite different. Determining a model for CMM measurements using classical error budgeting is a formidable task and is nearly impossible to capture all potential contributors and their sensitivities.

As an alternative to classical error budgeting for CMM measurements, dedicated national standards and technical specifications are available to aid in the testing and analysis of determining task-specific measurement uncertainty [3–5]. These documents include an overview and metrological definitions, methods of experimental correlation to calibrated workpiece measurement, and requirements for simulation software packages. The series is designed to eliminate the need for a full mathematical model of the measurand,

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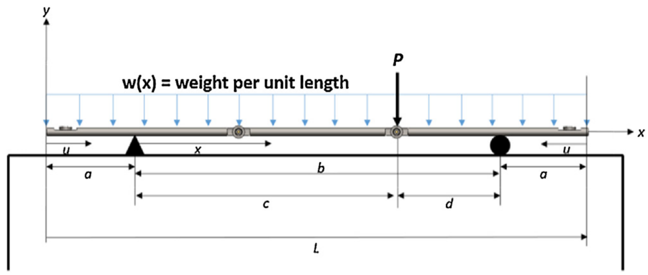

Fig. 1. Setup of simply-supported predictive model.

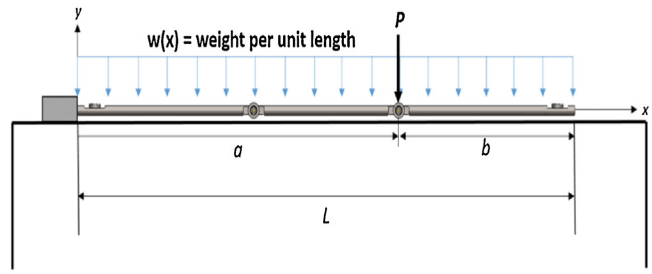

Fig. 2. Setup of cantilever predictive model.

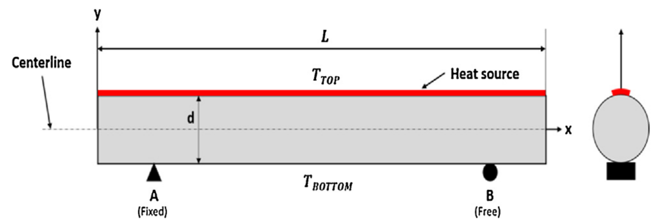

Fig. 3. Schematic of thermal testing setup.

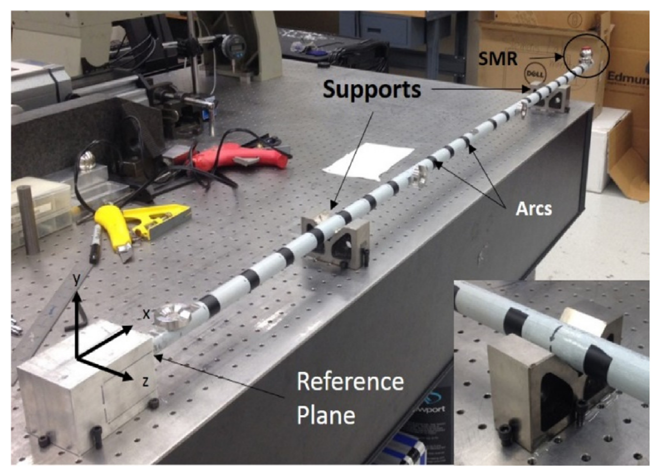

Fig. 4. Experimental setup for simply-supported model.

yet still be in compliance with the GUM to establish uncertainty estimation for a specific measurand.

Of all the influence sources that contribute to the measurement uncertainty, extrinsic effects are most difficult to quantify. This is the result of these factors generally being outside the control of the CMM manufacturer and user. Extrinsic effects that affect the task-specific uncertainty are factors such as non-ideal workpiece geometry, contamination, workpiece fixturing, and variation among the operators. These influences are usually quantified using expert judgement or Type-B evaluations as the GUM describes.

The purpose of the work described in this paper is to investigate the separation of predictable biases introduced by the workpiece and environment from the quantifiable, but random, errors introduced by the same. Furthermore, instrument bias is treated as insignificant in comparison to workpiece error and extrinsic effects. This work specifically addresses the uncertainty contributors due to the extrinsic effects of workpiece deformation due to gravitational loads, and of thermal distortion due to inhomogeneous temperature of the workpiece.

3. Predictive modeling of extrinsic effects

The predictive models for the extrinsic effects under investigation are developed using common engineering techniques such as beam theory and finite element analysis (FEA). Each of the workpiece geometries used for modeling has a circular cross-section along the entire length; therefore, the center line (axis) of each can be modeled. Each case is simplified to a two-dimensional investigation of the workpiece center line to determine whether our preliminary modeling is adequate.

3.1. Sag due to gravitational loads

Gravitational sag can have significant effects on workpieces which are massive or have high aspect ratios, and tend to bend under their own weight. Therefore, uncorrected sag can be a relatively large uncertainty contributor as an unknown bias. If corrected, then the uncertainty contribution is related to the quality of our model. In some industrial environments, sag is corrected using dial indicators and lifts for some large-scale workpieces, but is often left uncorrected.

Sag due to gravitational loads is nonlinear in its complete form but first-order approximations can be carried-out using Euler-Bernoulli beam theory [6] to model the deflection of a beam center line analytically. The workpiece used in our sag experiment, a long steel rod with calibrated point locations, was treated as a beam with a circular cross-section and multiple point load locations. Two load cases are used for investigating center line deflections: a simply-supported case with symmetric overhang (Fig. 1), and a cantilever case (Fig. 2). Both cases are modeled with a uniformly distributed load (the weight of the workpiece, *w(x)*) and a concentrated point load (i.e. weight of spherically mounted retroreflector (SMR), *P*).

To determine the center line experimentally, a straightforward reversal technique is performed [7]. The deflection of the rod is measured in two rotations about its axis, effectively reversing the action of gravity on the rod. The mathematical model for the center line due to gravity, *R(x)*, is calculated using Eq. (1),

$$R(x) = \frac{M_0(x) + M_{180}(x)}{2} \tag{1}$$

where $M_0(x)$ is the measurement in the 0° position and $M_{180}(x)$ is the measurement in the 180° position. In using a reversal to determine the centreline, most of the systematic errors attributed to gravitational effects are eliminated from the measurement results. Of course, there is a possibility of some systematic effects (unknown) still influencing the measurement results. These remain as part of the measurement uncertainty.

The correctness of the model is verified by calculating the difference (error) of the predicted center line compared to the experimental center line measurement as shown in Eq. (2),

$$\Delta Y = Y_P(x) - R(x) \tag{2}$$

where $R(x)$ is the center line of the experimental measurements and the $Y_P(x)$ is the predicted center line. This error is not a result of only the measurement uncertainty, but in the ability to model the