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Optimal inspection strategy planning for geometric tolerance verification

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ABSTRACT

Two features characterize a good inspection system: it is accurate, and compared to the manufacturing cost, it is not expensive. Unfortunately, few measuring systems posses both these characteristics, i.e. low uncertainty comes with a cost. But also high uncertainty comes with a cost, because measuring systems with high uncertainty tend to generate more inspection errors, which come with a cost.

In the case of geometric inspection, the geometric deviation is evaluated from a cloud of points sampled on a part. Therefore, not only the measuring device has to be selected, but also the sampling strategy has to be planned, i.e. the sampling point cloud size and where points should be located on the feature to inspect have to be decided. When the measuring device is already available, as it often happens in geometric measurement, where most instruments are flexible, an unwise strategy planning can be the largest uncertainty contributor.

In this work, a model for the evaluation of the overall inspection cost is proposed. The optimization of the model can lead to an optimal inspection strategy in economic sense. However, the model itself is based on uncertainty evaluation, in order to assess the impact of measurement error on inspection cost. Therefore, two methodologies for evaluating the uncertainty will be proposed. These methodologies will be focused on the evaluation of the contribution of the sampling strategy to the uncertainty. Finally, few case studies dealing with the inspection planning for a Coordinate Measuring Machine will be proposed.
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1. Introduction

For any company, quality is one of the main factors in the competition to become the leader of the sector. Even if quality has often been considered only as “product quality”, “process quality” should be considered, too, because a good process usually produces good products with even lower costs. Anyway, to ensure goodness of product/process quality, some control has to be performed, i.e. a quality system has to be established. Every quality system is essentially based on the observation of the product/process: a quality characteristic is *measured*, and from this measurement the behavior of the system is decided to be “good” or “not good”. This may imply also that a defective part is rejected, or that the whole process has to be checked and adjusted, if required. From now on, just the problem of checking parts will be considered. The possibility of rejecting a part due to the quality inspection leads to some unexpected costs. Inspection of parts consists in comparing the actual result of some measurement performed on it with a “specification limit” *SL*. Due to measurement error [1] it is possible that a good part (namely a part complying with the *SL*) is rejected (type A error), or a defective part is accepted (type B error) [2]. Both these types of errors come with a cost.

Inspection error probability is strictly related to uncertainty [3]. But high accuracy measurements are more expensive than low accuracy measurements, so reducing inspection errors frequency (which implies the choice of low uncertainty measurements) will increase measurement costs: a trade-off between inspection error costs and measurement costs has to be defined.

1.1. Geometric tolerances and compliance to tolerances

In mechanical engineering, a quite common specification is a “geometric tolerance” [4,5]. A geometric tolerance states how much a real part can differ from its ideal, designed geometry; therefore, a geometric tolerance usually defines only an upper specification limit for the geometric deviation. Geometric tolerances importance is increasing because of the performances the market requires to mechanical systems: if dimensional tolerancing may suffice simple parts to ensure functionality of simple parts, more complex fits require well-structured definitions.

Of course, the check of a geometric tolerance involves the estimate of the geometric deviation, and an uncertainty evaluation

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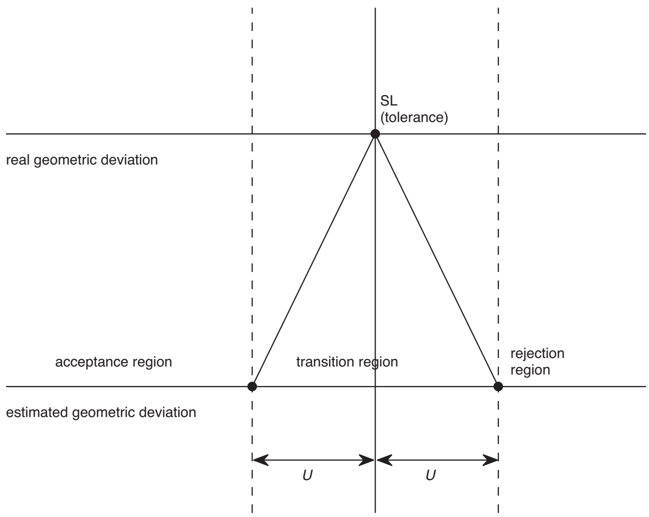

Fig. 1. Regions according to the ISO 14253-1 standard.

has to be proposed for this estimate. Some international series of standards have been proposed giving guidelines for this evaluation, like ASME B89.7.3 [6–8] and ISO 14253 [9–11]. In particular, ASME B89.7.3.1 [6] and ISO 14253-1 [9] propose "guidelines for decision rules" for "considering uncertainty in determining conformance to specifications". A decision rule should essentially identify three regions for the measurement result [12,13]:

1. *Conformance zone*. If the measurement result falls in this zone, then the related part is accepted.
2. *Non-conformance zone*. If the measurement result falls in this zone, then the related part is rejected.
3. *Uncertainty range*. If the measurement result falls in this zone, it is not possible to state whether the part conforms or not to the tolerance.

ASME B89.7.3.1 and ISO 14253-1 differ in that the ASME standard gives only guidelines on how to choose these regions, because the selection of a decision rule is considered a business decision, and the flexibility of having a continuum of rules ranging from stringent to relaxed acceptance or rejection is needed in order to satisfy a broad range of industries; ISO standard instead rigidly states that a part should be accepted if its geometric deviation estimate is lower than the geometric tolerance reduced by the expanded uncertainty U, and rejected if its geometric deviation estimate is greater than the geometric tolerance augmented by U. The region $(LS - U, LS + U)$ is the uncertainty range (Fig. 1). In particular, the standard states that, if a supplier has to prove conformance, a part falling in the transition region cannot be considered conforming, while, if a costumer wishes to prove non-conformance, a part falling in the transition region cannot be considered non conforming.

1.2. Evaluating geometric deviation

Traditional instruments are not suitable to check geometric tolerances. Geometric tolerances verification is usually performed by means of coordinate metrology. A wide range of coordinate measuring devices exist today on the market, distinguished by their accuracy, working principle (mechanical contact, laser triangulation, image probing,. . .), sampling (point-to point, line scanning, area scanning), measuring volume, etc. Regardless of the specific instrument, every coordinate measuring system is based on sampling some points on the surface to inspect. Then, a "substitute geometry" is fitted on these points, and the geometric deviation is evaluated as the maximum deviation from this geometry (see the work by Anthony et al. [14] for further details). Because only few points usually define the amplitude of the tolerance zone, only these points are really relevant to evaluate the geometric deviation.

Most coordinate measure system are flexible, being able to sample points on very different surfaces. However, this flexibility makes evaluation of measurement uncertainty difficult since different measurement tasks are characterized by different uncertainties; hence, a "task specific uncertainty" [15] should be evaluated. In fact, Wilhelm et al. [15] have identified several sources of Coordinate Measuring Machine (CMM) measurement uncertainty such as hardware, workpiece geometry, sampling strategy, fitting and evaluation algorithms, and extrinsic uncertainty sources. In particular several authors have pointed out that the sampling strategy can significantly affect measurement uncertainty (see e.g. Weckenmann et al. [16,17]; Kruth et al. [18]), in particular when the sample size is small, which may be a typical situation if uncertainty cost has to be optimized. Because sampling strategy is most often determined by the operator, it is the main leverage to control uncertainty as well. A comprehensive discussion about coordinate measuring devices performance, uncertainty evaluation, and relationship with the conformance or non conformance statement can be found in the recent work by Phillips [13] in the book by Hocken and Pereira [19].

Methodologies for sampling strategy planning may be grouped into three categories (for further reference on sampling strategy planning, please address to recent works of the authors of the present paper [20,21]). Blind sampling strategy are standard sampling strategies, like those defined in international standards [22–25], which do not require any knowledge of the surface to inspect, apart from nominal geometry. Adaptive strategies [26,27] try to "adapt" the strategy itself to the actual surface, that is, they sample an initial set of points, and then sequentially choose the next sampling points based on the knowledge of the already sampled points. Finally, manufacturing based sampling strategies are strategies developed for parts manufactured by a specific process [28].

Manufacturing based sampling strategies originate from the observation that sampling strategy uncertainty contribution and the actual part geometric deviation tend to be closely interrelated [15,18,29]. If geometric tolerance definitions given by the ISO 1101 standard are followed, only those zones of the surface which deviate the most from the design nominal geometry define the geometric deviation (worst case scenario). There is a strong interrelations between sampling strategy, measurement point layout and capability to identify part out-of-tolerance ("anomalous") zones caused by part geometric deviation patterns that directly affect measurement uncertainty. There is an extensive literature related to development of a generic methods for optimization of measurement point layouts [30–33]. However, it has also been observed that anomalous zones of the part profile/surface tend to be the same throughout the production. It may therefore be stated that the part presents a process inherent error signature – a "manufacturing signature".

Ceglarek et al. [34,35] developed methods to model part variation patterns of pre-assembled components to compensate dimensional variability caused by upstream manufacturing processes. In recent years several studies have suggested that the interaction between sampling strategy and manufacturing process error signature can be analyzed in order to generate very effective sampling strategies (e.g. Summerhays et al. [36], Killmaier and Babu [37], or Colosimo et al. [28]). However, the criteria adopted for the definition of the optimal strategy are heuristic, and lack an explicit uncertainty evaluation.

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