# Short Papers

## Statistical Estimation and Testing for Variation Root-Cause Identification of Multistage Manufacturing Processes

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*Abstract*—**Root-cause identification for quality-related problems is a key issue in quality and productivity improvement for a manufacturing process. Unfortunately, root-cause identification is also a very challenging engineering problem, particularly for a multistage manufacturing process. In this paper, root-cause identification is formulated as a problem of estimation and hypothesis testing of a general linear mixed model. First, a linear mixed fault-quality model is built to describe the cause–effect relationship between the process faults and product quality. Then, the estimation algorithms developed for a general linear mixed model are adapted to estimate the process mean and variance. Finally, a hypothesis testing method is developed to determine if process faults exist in terms of statistical significance. A detailed experimental study illustrated the effectiveness of the proposed methodology.**

*Note to Practitioners*—**Economic globalization brings intense competition among manufacturing enterprises. The key to succeed in this competitive climate is to rapidly respond to fast-changing market demands with high-quality and competitively priced products. To achieve this, we need to quickly identify root causes of quality-related problems in a complicated manufacturing system. However, the current widely adopted quality-control techniques focus more on monitoring than on root-cause identification. These techniques can efficiently detect the changes in the process but the root cause identification is often left to the plant engineers or operators. In this paper, a systematic estimation and testing method is proposed to identify the variational root causes in multistage manufacturing processes. First, a linear model is built based on the design information to describe the cause-effect relationship between the process faults and product quality. Then, an algorithm is developed to estimate the mean and variance of the process faults from the quality measurements of products. Finally, a statistical testing method is developed to determine if process faults (i.e. root causes) exist in terms of statistical significance. A detailed experimental study illustrates the effectiveness of this method. The method presented in this paper is a new quality-control technique and can be used for quality improvement of multistage manufacturing processes.**

*Index Terms*—**Linear mixed model, multistage manufacturing process, root-cause identification, variation propagation.**

### I. Introduction

Root-cause identification for quality-related problems is a key and necessary step for the operation of manufacturing processes, especially the high-throughput automated processes. Root-cause identification is also a challenging engineering problem. This is particularly true for the multistage manufacturing processes, which is defined as a process that produces the products under multiple setups. The quality information flow of the product in a multistage manufacturing system and the interaction between the process faults and the product quality characteristics are very complicated. The effect of certain process fault on the product quality could propagate along the process, and different process faults could have the same manifestation on the product quality. An example of a two-stage machining process is shown in Figs. 1 and 2.

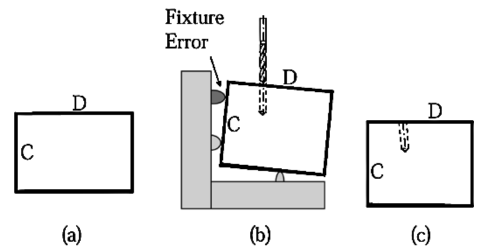


Fig. 1. Effect of fixture error.

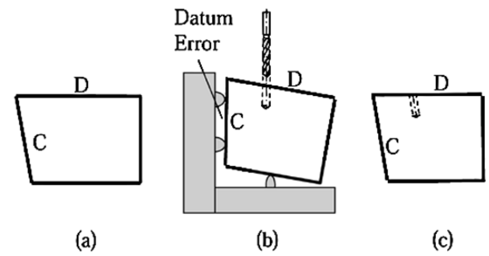


Fig. 2. Effect of datum error.

The workpiece is a cube of metal (the front view is shown). Surface C of the workpiece is milled in the first step [Fig. 1(a)]. The hole is drilled in surface D in the second step [Fig. 1(b)]. Due to an error in the locating pins of the fixture in the second step, the resulting hole is not perpendicular to surface D, as shown in Fig. 1(c). In this example, the perpendicularity of the hole is the product quality characteristic and the quality-related problem is caused by the fixture error, so-called "root cause" or "process fault." In most cases, the process root causes are not directly measurable and have to be identified based on product quality measurements. For a multistage process, the identification is not straightforward. For example, in the process illustrated in Fig. 2, the resulting hole is not perpendicular to surface D [Fig. 2(c)] either. However, the root cause is not the fixture error in the second drilling step [Fig. 2(b)]. Instead, the root cause is the process fault in the first milling operation [Fig. 2(a)]. In other words, the process faults in a multistage process might propagate along the process to the downstream stages. This paper focuses on a systematic method of root-cause identification using product quality data of multistage machining processes.

Statistical process control (SPC) [1], [2] is the main technique frequently used in practice for process quality control. In the SPC scheme, measurements of product quality characteristics are taken from the finished or intermediate product, and they are treated as random variables. The key parameters of their statistical distribution such as the mean value and variance are compared with those under normal conditions. If the differences are larger than pre-specified thresholds, an alarm is generated to indicate that some changes happen in the process. Although

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