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An approach to computer-aided quality control based on 3D coordinate metrology

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Abstract

The quality of manufactured products usually needs to be verified. This paper presents an advanced CAQ approach to compare manufactured objects with reference data from underlying CAD models. First, an overview about the current state-of-the-art in optical 3D measurement techniques is given. After that the research method adopted in this paper is discussed. Furthermore, a software prototype of the presented approach in which a stripe projection system with combined gray-code and phase shifting is described. With this equipment, 3D shapes of objects or manufactured products can be measured. In order to compare the 3D data (represented in sensor coordinate system) a registration to the CAD coordinate system is needed. At first, the selection of a starting point for the orientation parameters is described. For the registration process different numerical algorithms are used to minimize a distance function. To achieve a better performance, an optimization process based on 3D voxel arrays is introduced. After the registration process, several parameters for the kind of geometric displacement can be calculated and visualized. For objects that cannot be measured from one direction, a pair-wise registration as well as a global registration have been developed. Furthermore, some rapid prototyping examples to which our CAQ approach has been applied are presented. Those examples show that our method works well in practice. Finally, some application fields for the CAQ approach presented here are outlined. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Computer-aided quality control; Computer-aided manufacturing; Rapid prototyping; Coded light approach; 3D coordinate metrology

1. Introduction

In recent years the entire process from computer-aided product design to manufacture has reached an almost ultimate perfection. However, nominal/actual value comparisons show that there are always deviations between a manufactured product and its underlying CAD model. Reasons for that are, e.g. tool wear, thermal expansion, material defects, etc., things that are due to the nature of mechanical engineering, of course. In the range of computer-aided quality control the above-mentioned deviations have to be verified to detect part variations or to make tolerance conformance decisions. Today, there are powerful state-of-the-art coordinate measurement systems available that have provided industry with outstanding tools for expecting complex parts. Meanwhile, the majority of these systems is based on 3D metrology that has brought a significant change in modern coordinate measurement. The major difference to traditional measurement methods is that 3D metrology systems generate surface coordinates of a measured part instead of measuring its geometric dimensions. Having a collection of digitized surface points, details concerning part variation can be observed. Furthermore, various sections of different geometric features can be measured in a single process. Once a set of measurement data is collected, an independent numerical analysis must be performed to find a basis for a subsequent comparison between the measured feature and the corresponding reference data from its CAD models counterpart. This is the main goal of the approach presented in this paper. A more comprehensive introduction to 3D metrology as well as an overview about related work in this field can be found in [8].

This paper presents a non-contact metrology approach that can be used for various tasks in computer-aided quality control and rapid prototyping. It will be discussed throughout the whole paper and can be summarized as follows. Manufactured objects are measured by a stripe projector

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system based on a coded light approach combined with phase shifting. For image acquisition a standard video camera is employed. The sampled surface points measured in sensor coordinate system, typically 200.000–400.000 per image, are transferred into a CAD coordinate system. After selecting a rough orientation, either in an interactive manner or by a priori knowledge (automatic orientation without a priori knowledge can also be achieved by using fixed marks on the object's surface), a sophisticated numerical optimization process is started to determine the exact orientation that means to align the CAD model and the measured data set. A problem that occurs whenever objects cannot be captured from a single 3D sensor within one image has been solved by applying an additional orientation process. Measured data sets captured from different directions can either be orientated relatively to each other or transformed into a common coordinate system. For a nominal/actual value comparison, the distance from the data set to the underlying CAD model can be calculated point by point. The evaluated results can be visualized in many statistical ways, e.g. as difference per measured point, minimum, mean or maximum difference within a CAD element (e.g. an STL triangle).

The approach proposed in this paper has been successfully applied to several stereo-lithographic rapid prototyping objects and produced remarkable results. It supports quality control for all kinds of rapid prototyping and/or NC manufactured objects and is especially suited for an integration of CAQ into CAM processes. In that way two essential independently performed processes can be combined to make the overall process of product development more efficient.

2. Methods and principles

2.1. 3D coordinate measurement

Today, there are various measurement systems available which are based on very different approaches. These measurement techniques can be classified into active and passive methods. In general, passive approaches are used to calculate the shape of an object by interpreting rather special object characteristics. These methods usually depend on precise a priori knowledge of the related objects and therefore are not appropriate to meet general industrial requirements. Hence, they will not be discussed here in more detail.

Active measurement methods usually do not depend on special object characteristics and can be classified into contact and non-contact methods. An example of a contact system is the classical CMM (coordinate measuring machine) that samples discrete points of the related part using a mechanical sensor. To capture a complete shape, the sampling has to be performed in two directions. Although this method provides maximum accuracy, it is quite time consuming and cannot be used for soft materials that must not be touched. Therefore, it does not always meet contemporary industrial requirements. More relevant to industrial needs are non-contact systems. They will be considered further on in this paper, the focus being on optical non-contact methods. Beyond those, there are further methods that might be applicable as well, e.g. microwave-based radar or ultrasonic-based measurement, but they are not relevant for the research method adopted in this paper.

The majority of employed systems is based on the following principles: spot triangulation, stripe sectioning, coded light approach, and interferrometrical methods. Since the last three methods are restricted to reflective materials, they are not well suited for general purposes. Hence, they will not be specified here, in contrast to the triangulation methods that will be considered in more detail.

Within the triangulation principle a point on an object surface can be determined by the trigonometric relations between a camera, a projector and the object itself (cf. Fig. 1). Suppose that all geometric parameters are known, the distance from the baseline to the object can be calculated according to Eq. (1):

$$d = b\frac{\sin\alpha\sin\beta}{\sin(\alpha+\beta)} \tag{1}$$

For a complete object digitization the projected spot has to be moved in two directions to sample the object in lines, point by point. This kind of sampling can be realized, e.g. by employing two sweeping mirrors. Obviously, the measurement accuracy is highly influenced by the angular precision of the spot movement mechanism. According to this, the error propagation of the depth measurement error Δd can be calculated according to (Eq. (2)):

$$\Delta d = b\frac{\sin^2\beta\,\Delta\alpha + \sin^2\alpha\,\Delta\beta}{\sin^2(\alpha+\beta)} \tag{2}$$

Since the spot direction α is fixed, only the parameter β needs to be determined. For spot triangulation, usually 1D sampling devices (sensors), such as line cameras or PSDs are employed. A comprehensive discussion of the mathematical background can be found in [4].

To overcome the limitation of single point scanning, the so-called stripe-shaped illumination method can be employed. Hereby a plane of light intersects an object and the corresponding image is a profile. A standard camera

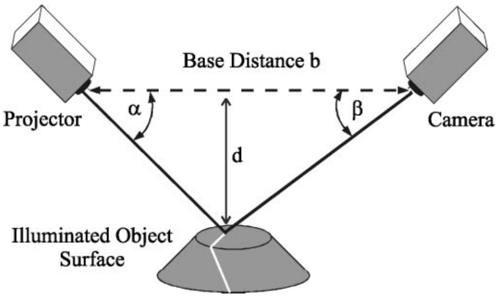

Fig. 1. Triangulation principle.