Simulation of geometrical errors during application of a confocal sensor system for the measurement of large components with high aspect ratios

Uwe Teicher[1], Christian Gollee[1], André Seidel[1], Steffen Ihlenfeldt[1,2]

[1]*Fraunhofer Institute for Machine Tools and Forming Technology IWU, Dresden, Germany*

[2]*Institute of Mechatronic Engineering, Technische Universität Dresden, Dresden, Germany*

Abstract

Machining of large components for the aerospace industry requires, in addition to sophisticated machining strategies a targeted monitoring of the machining quality due to the enormous demands on precision. For the acquisition of the as-is geometry after single machining steps, a non-contact system based on a confocal chromatic sensor was developed, with whose help the as-is geometry can be compared with the target geometry even in deep cavities at aspect ratios up to 40. The sensor system is coupled with the standard interfaces to a machine tool and performs measuring cycles based on modified NC programs. Data acquisition is done with a control-connected EDGE system. The result of the target/as-is comparison is the basis for CAM planning for subsequent machining. In addition to the design of the measuring system and the integration into the ecosystem of the machine system, a concept to calibrate the measuring system for operation on the machine tool was developed. Based on a simulation model of the measurement system various aspects of the calibration approach were analysed.

1 Introduction

Machining of structural components for the aerospace industry constitutes an enormous challenge, especially for large-scale components in batch size 1. One approach to solve this problem is the use of cyber-physical production systems in combination with digital twins [1]. This includes high-precision ISO 230 certified machine tools as well as the use of high-quality cutting tools [2]. However, a prerequisite is the knowledge of the divergence of the geometric as-is shape, which occurs due to residual stress-induced deformations [3] or even tool-deflection-induced deviations [4] measured by means of laser triangulation units [5] and the preparation of the data for a subsequent semi-automated machining [6]. This study presents a sensor system coupled into a machine tool to measure structures with large aspect ratios. The basis for the applicability of the system is a calibration. The procedure and the simulation of the error behaviour is the subject of this study.

2 Metrology system

The developed sensor system is based on a confocal chromatic distance sensor with a maximum sampling rate of up to 6.5 kHz and a dynamic resolution of 460 nm. It enables fast measurement cycles to be performed by means of specific NC programs. To measure components with large aspect ratios and deep cavities, the sensor is coupled to one end of a stiff CFRP tube. The other end is attached to the bottom of an aluminum housing. The housing contains the sensor controller and a bus coupler for integration into an EDGE device. The sensor system can be coupled and decoupled into the spindle of the machine tool with a HSK63 quick coupling. Figure 1 shows the entire sensor system on the left and a demonstrator workpiece (right). Black circles mark the places where misalignments can occur during assembly of the individual components.

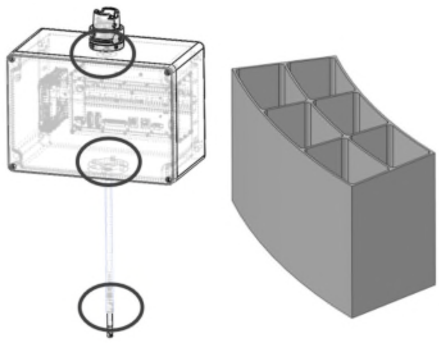

Figure 1: Sensor system with marked misalignments (left) and demonstrator workpiece with deep cavities (right)

3 Sensor system calibration approach

The confocal chromatic sensor determines one-dimensional distance values. When the sensor system is connected to the spindle of the machine tool, there is a deviation of the sensor longitudinal axis from the spindle axis due to the locations marked in Figure 1 caused by manufacturing inaccuracies. This deviation consists of a lateral offset in x- and y-direction combined with a misalignment around the same axes. If this offset is not taken into account, the fusion of the one-dimensional sensor data into a global three-dimensional point cloud in the machine coordinate system will result in deviations from the actually recorded geometry. To determine the offset, a calibration of the sensor system is performed. For this purpose, a digital image of a calibration standard in the form of a surface model is created using an independent high-precision measuring device. The surface of the calibration standard is then measured with the sensor system. Distance measurement values acquired in this way are transferred from the sensor system to the calibration standard coordinate frame following Eq. 1.

$$\vec{e} = {}^{T}\vec{p}_{measured} - {}^{T}\vec{p}_{surface} = {}^{M}\mathbf{T}_{T}^{-1} \cdot {}^{M}\mathbf{T}_{C} \cdot {}^{C}\mathbf{T}_{R} \cdot {}^{R}\mathbf{T}_{S} \cdot {}^{S}\vec{p}_{measured} - {}^{T}\vec{p}_{surface} \qquad (1)$$

In the calibration standard coordinate frame, the error $\vec{e}$ is minimized by varying the transformation parameters of the structural loop, see also [5]. In this way, the parameters of the structural loop can be determined that best represent the real misalignments. Figure 2 shows the structural loop used to transform the one-dimensional distance values of the sensor into the coordinate frame of the calibration target object.

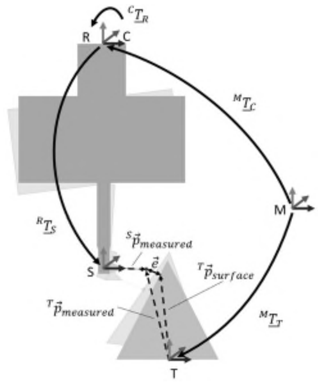

Figure 2: Structural loop with coordinate frames

4 Simulation

A simulation model of the distance measurement process was developed in *Python*, that uses free libraries which allow geometric operations to be applied to imported surface models. The simulation model allows verification of the calibration routine as well as the detection of errors in both the implementation of the structural loop and in the path planning.

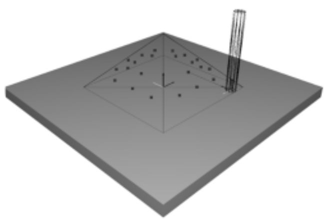

Figure 3: Simulation based generation of measurement data for sensor assembly calibration

A minimal parameter set is now available, which only contains parameters that do not correlate with each other. Furthermore, the influence of a certain shape of the calibration target object on the conditioning of the identification problem can be determined and different calibration targets can be compared. Furthermore, the robustness of the calibration method against the impact of noise on the achievable accuracy in parameter identification can be investigated. Figure *3* illustrates the simulation model. The pyramid represents the calibration target and the cylinder represents the sensor. The dots on the surface depict the measurement points.

5 Discussion

The presented method of a comprehensive geometric detection with the help of a confocal chromatic sensor of a machine system, which is also used for machining at the same time, represents an enormous opportunity for large components to realize lot size 1. The study provides a basis for system analysis by demonstrating a calibration routine and analyzing it simulatively with regard to possible error scenarios. Subsequent work will deal with the technical design of the sensor system and its implementation in the machine and control ecosystem.

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