Measurement 73 (2015) 239–246

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

Evaluation of system models for an endoscopic fringe projection system

Steffen Matthias *, Markus Kästner, Eduard Reithmeier

Institute of Measurement and Automatic Control, Leibniz Universität Hannover, Nienburger Str. 17, 30167 Hannover, Germany

ARTICLE INFO

Article history:
Received 31 January 2015
Received in revised form 29 April 2015
Accepted 27 May 2015
Available online 2 June 2015

Keywords:
Endoscopy
Fringe projection
Calibration
Metal forming
Inline inspection

ABSTRACT

To be able to perform inline inspection of complex geometries, which exhibit for example undercuts or internal structures, a new endoscopic micro fringe projection system has been developed. It is designed to perform areal measurements for tool inspection inside the limited space of metal forming presses by employing flexible image fibers to couple the measurement system's camera and projector to a compact sensor head. The projector features a laser light source and a digital micro-mirror device to generate high-contrast fringe patterns. To increase the depth of field of the sensor heads, custom gradient-index lenses have been designed as an approximation to the Scheimpflug principle. Challenges arise for both calibration and phase measuring algorithms from the optics, as well as from the reduction in resolution introduced by the fiber bundles. This paper presents an evaluation of two different system models for the endoscopic fringe projection system, which are based on the pinhole camera model and a black box model. An automated calibration process, which gathers the calibration data for two calibration algorithms that are robust to artifacts introduced by the optical path, is demonstrated. Based on a comparison of measurements, differences between the two modeling approaches are discussed. Finally, results of measurements of a demonstrational metal forming tool are shown as an application example.

1. Introduction

Modern production processes aim to manufacture complex goods at low costs. In the field of metal forming, complex geometries are usually manufactured using independent forming steps, such as deep-drawing and bulk-forming [1]. The goal of the research within the Collaborative Research Center TR 73, supported by the German Research Foundation (DFG), is to combine different metal forming techniques to reduce production times and costs in an automated process [2]. Fig. 1 shows a drawing of the TR 73 demonstrational forming tool for a combination of deep-drawing and bulk-forming of sheet metal. To keep rejection costs at a minimum, holistic quality control of both parts and forming tools is desired for the process. This implies high requirements for the measurement systems, as measurement times in the range of one second or less are demanded. Optical technologies are preferred for the task because of their ability to obtain contact free geometry data while meeting the time restrictions [4]. To meet these requirements, a number of endoscopic technologies are under research. Different approaches, such as passive stereometry, structured light, confocal techniques, digital holography or the time-of-flight-principle show promising results [5,6]. Fringe projection profilometry, which uses structured light to measure 3D data, is able to perform areal geometry inspection of larger features [7]. However, commercially available systems struggle to

* Corresponding author.
E-mail address: steffen.matthias@imr.uni-hannover.de (S. Matthias).

http://dx.doi.org/10.1016/j.measurement.2015.05.024
0263-2241/

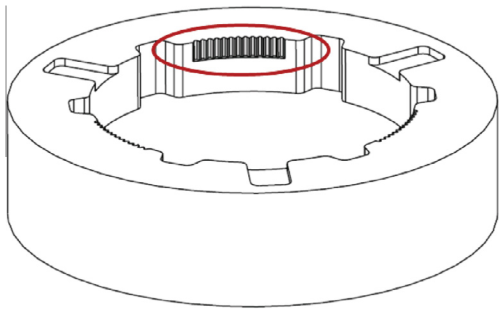

Fig. 1. TR73 sheet bulk-metal forming demonstrational tool [3].

measure complex geometries with undercuts or inner functional elements due to positioning limitations. As the technology is based on the triangulation principle, positioning of the measurement system to the specimen is crucial [8]. Shadowing and non-optimal measuring angles lead to incomplete or noisy geometry data. The endoscopic fringe projection system described in this paper is capable of obtaining areal measurements within the limited space of a forming press by using a very compact sensor head and flexible endoscopes, while the programmable pattern generator allows to reduce measurement times by projecting object-adapted patterns. Depending on the task at hand, different designs of the sensor head can be applied to adapt to the geometry to be inspected. The fringe projection patterns are guided from the sensor head to a base unit, which contains a digital laser projector and camera, using flexible image fibers. The components of the system, such as image fibers and gradient-index (GRIN) lenses lead to artifacts which are unusual for fringe projection profilometry. Due to the image fibers, pattern resolution is reduced, while the custom designed GRIN lenses exhibit asymmetric lens distortions. In order to obtain accurate measurement results, these conditions need to be considered in the mathematical models used to calculate 3D point data from measured phase-maps. Furthermore, the corresponding calibration algorithms need to be robust to noise in the calibration data. This paper describes the considerations for choosing an appropriate system model to obtain metric measurements with the endoscopic system as well as a comparison of two different system models.

2. System design

The basic concept of the endoscopic fringe projection system consists of a base unit, which houses the projector and camera, and a compact sensor head which is coupled to the base unit using image fibers.

2.1. Projector

The projector part of the fringe projection system is illuminated using a 532 nm single mode laser light source with an output power of 50 mW to enable fast measurement times. In addition to its high light intensities, the laser is well suited for efficient fiber coupling. However, interference patterns, the so called speckle, appear when projecting the coherent laser light onto technical surfaces. A former design of the projector employed a rotating diffusor to reduce laser speckle effects [9]. In the current setup of the system, the rotating diffusor element has been replaced with a diffusor by Optotune, which performs the diffusor displacement with electrostatic polymers. Therefore it eliminates unwanted vibrations in the systems base station, while maintaining a good reduction of the speckle intensity. Following the speckle reducer, two micro-lens arrays are positioned in the beam path to shape a flat-top beam profile to enable an even brightness distribution of the fringe patterns. The projector is capable of generating arbitrary fringe patterns by using a digital micro-mirror device (DMD) by Texas Instruments. The DMD features a resolution of 1024 by 768 pixel and is able to display up to 291 patterns per second with a gray-scale resolution of 8 bit.

2.2. Camera

The camera unit uses a Point Grey GRAS-50S5M-C gray-scale CCD sensor with a resolution of 5.0 mega pixel. To allow for fast measurement times and exact exposure control, the camera is synchronized to the projector hardware using a trigger signal. For fiber outcoupling, a standard microscope objective lens with 4X magnification is used. In order to achieve full illumination of the camera sensor, a custom fiber and objective mount has been designed. The benefit of using a high-resolution camera in combination with the fibers with relatively low resolution is the possibility to capture the fibers grid structure to avoid aliasing effects. A specifically designed lowpass filter is used to remove the fibers grid effect and noise in the camera image, such as remaining speckle transported by the multi-mode fibers, followed by a downsampling step. This leads to reduced processing times of phase-map and 3D-data by removing redundant information. The typical number of phase-map data points processed for calculating 3D point data is about 180,000. A processed photo of the gearing on the TR 73 demonstrational tool can be seen in Fig. 2.

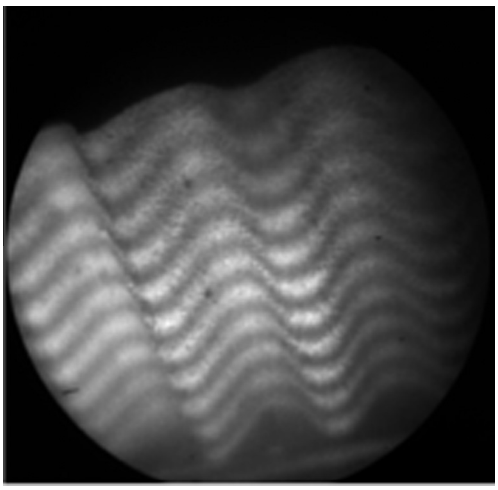

Fig. 2. Fringe image of the gearing features on the TR 73 tool.