Optics and Lasers in Engineering ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

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

Rigid and flexible endoscopes for three dimensional measurement of inside machine parts using fringe projection

Andreas Pösch*, Jochen Schlobohm, Steffen Matthias, Eduard Reithmeier

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

ARTICLE INFO

Article history:
Received 30 November 2015
Received in revised form
27 May 2016
Accepted 30 May 2016

Keywords:
Endoscopy
Endoscopic 3D measurement
Fringe projection
Structured light
Optical 3D metrology

ABSTRACT

Routine maintenance is mandatory for safe and efficient operation of complex machines, such as airplane turbines. Occasional special events, like bird strike, entail extraordinary inspection works. Hereby, inside machine parts are hard to reach, oftentimes occluded by other parts and not directly accessible for visual inspection. Disassembly of machine parts is time-consuming and expensive and, therefore undesired. This leaves distal imaging, i.e. endoscopy, to be the only practical option for defect detection. Ordinary endoscopes, which provide two dimensional intensity image data, are insufficient to fully assess the risks caused by small three dimensional defects. As a solution to this issue, we have developed and implemented two different systems for three dimensional endoscopic measurement based on structured light projection which are capable of recording high resolution and high accuracy point cloud data. A measurement standard deviation of roughly 20 μm is achieved within a field of measurement of $20 \times 30 \times 30\ \text{mm}^3$.

1. Introduction

Many complex machines, such as airplane turbines, suffer from wear and are exposed to the risk of damage from external imminence of solid particles which are sucked through the turbine duct for instance within a bird strike event or from strongly abrasive airborne particles carried by a sandstorm in desert areas. As a consequence, the assessment of those complex machines is a routine operation within the scheduled maintenance processes or sometimes even additionally carried out on suspicion of acute damage. Sensitive inside machine parts and structures of complex machines are oftentimes mechanically and visually hard to reach. In many practical cases disassembly of the machine for inspection purposes is a time consuming and expensive task and therefore undesired. Consequently, visual detection and characterization of possible defects and abrasions is best feasible via distal imaging, i.e. endoscopy. Conventional endoscopy allows the capture of two dimensional intensity images from the machine part in question with the help of artificial illumination. The image is typically applicable for manual visual inspection by trained technicians or computationally analyzed by image processing algorithms.

One of our most important design goals was to establish a measurement system which, in contrast to the above mentioned available systems, allows to obtain reliable and particularly traceable three dimensional geometric data with high resolution. No large blind spot at the endoscope tip, i.e. no frontal overhang parts should be present. Furthermore, we intend to characterize the systems thoroughly. According to that, we developed methods for three dimensional measurement based on the well-known fringe projection technique [1,2].

Dents, break-offs and deep scratches, which all produce high intensity contrasts in the endoscope image, are well detectable kinds of defects in a conventional endoscopic image. The image data does, however, not come with three dimensional information about the suspected defects. This does not give objective geometric data about significant defect characteristics like depth, volume or aspect ratio of length vs. depth. Additionally, smooth-shaped errors such as dull indentations and abrasion cannot be identified reliably because they feature no edges or local contrast in the two dimensional image. Unfortunately, these kinds of defects are strongly associated with wear and abrasion [3] and, hence, occur very commonly.

In particular, we designed and fully implemented two different hardware realizations of endoscopic fringe projection systems. Both systems consist of very compact sensor heads while achieving high accuracy in three dimensional data acquisition. One system is based on high resolution flexible image fiber bundles and referred to as the *fiberscopic system* [4] and the other system is based on a combination of a rigid borescope together with a distal micro camera and named the *borescopic system* [5]. By using cold light projector designs with endoscopic distal projection we can benefit from high power light sources and a digital spatial light modulator design without any moving parts. Employing mainly

* Corresponding author.

http://dx.doi.org/10.1016/j.optlaseng.2016.05.023
0143-8166/

highly available stock components the total hardware cost of both systems is reasonably bounded, down to less than three thousand Euros for the borescopic system.

In this article, we show the setup and working principle on which both endoscopic fringe projection systems are based, and a first characterization of the measurement accuracy achieved.

2. Related work

There do exist previous approaches for 3D enabled endoscopy. The commercially available *Endoeye Flex 3D* laparoscope from Olympus is based on a passive stereo vision approach. Whilst this technology is suitable for medical investigations where the biological tissue usually provides high-contrast texture features for solving the registration problem; this cannot be assumed for technical parts with smooth metallic or ceramic surface areas. Here, only active triangulation systems are capable of performing reliable dimensional measurements. Such an active triangulation is realized with the *Multipoint* measurement endoscope from Karl Storz which has a built-in laser diode that projects 49 red dots into the field of view of a single view endoscope with the help of a diffractive optical element (DOE). Accordingly, the system is able to generate a maximum of 49 three dimensional measurement points. This point density is considered way too poor for the characterization of critical airplane parts. A third competing system is the *XLG3 VideoProbe* from GE which is capable of providing three dimensional measurements by not otherwise specified phase measurement, i.e. active triangulation. There is, as known to the authors, no clear information available about the resolution, point cloud density and accuracy achieved for the three dimensional results. The only statement about system accuracy that comes from the manufacturer is given on p. 112 of the manual [6]. There, a lateral deviation of $\pm 50\,\mu m$ on a 1.0 mm distance measurement and $\pm 127\,\mu m$ on a 2.54 mm distance measurement of a planar reference device are rated “good” for application. No information about distal measurement accuracy is provided.

In 2008, Albertazzi et al. [7] proposed their photogrammetric endoscope based on fringe projection for the measurement of inner cylindrical surfaces for the inspection of welded tube joints. The system configuration includes two wide angle cameras facing each other and one LED light source in between which is able to radially project a helical fringe pattern onto the inside of the measured cylinder hull. As the pattern generating structured slide can be rotated via a tiny motor, phase measurement is made possible. The system setup is enclosed in a transparent tube with 43 mm diameter and a length of 580 mm. Albertazzi et al. achieved a standard point deviation of 0.105 mm and a feature deviation of 31 μm for a fitting cylinder diameter. As the system contains moving parts, the miniaturization potential is limited and with the design of two facing cameras, the tube tip area can be considered a *blind spot*, i.e. blind holes cannot be measured to the bottom.

3. Fringe projection 3D measurement

Fringe projection is a non-contacting optical measurement technique which is based on the principle of active triangulation [8] and gives three dimensional point cloud data of an opaque object surface. In a state of the art setup, a digital video projector is utilized for structured illumination of the area of measurement [9]. As each pixel of the video projector is individually controllable in output intensity, it is possible to generate almost arbitrary illumination structures. For the purpose of three dimensional measurement, several sinusoidal bright and dark fringe patterns of different spatial frequency and phase are projected onto the specimen and observed with a digital camera from a different angle of view [10], see Fig. 1. From the captured image sequence it is possible to reconstruct a so-called phasemap [11] which gives the relation between projector and camera pixel positions (also known as disparity map) as input for the triangulation algorithm, see Fig. 4 for a scheme of the algorithm.

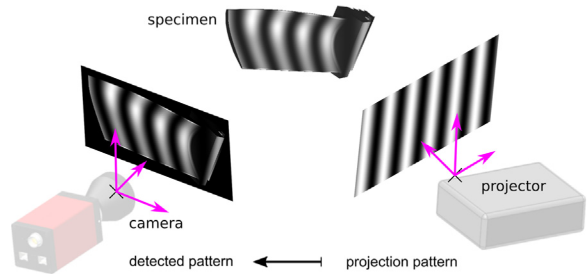

Fig. 1. Scheme of a typical fringe projection system consisting of a structured light projector and a camera for data acquisition both observing the same specimen surface are under different angles. While a sequence of structured light patterns is projected onto the object, the camera records the corresponding image frames of the diffuse reflexion as an input to the reconstruction algorithm.

In order to obtain metric three dimensional data, any fringe projection setup must be calibrated. For that purpose, two different system models are utilized, each in concert with a suitable calibration procedure for determination of all relevant model parameters. These models are, in particular, the well-known pinhole model with radial distortion as described by Tsai [12], see Fig. 2a, and a black-box calibration model, shown in Fig. 2b. In this context, the pinhole model is applied for the parameterization of either camera (of the fiberscopic and the borescopic system alike) and the borescopic projector whereas the projector of the endoscopic system is calibrated using a black-box model. The system models and calibration procedures are briefly depicted in the following.

The pinhole model is parameterized by the internal projection matrix $\mathbf{K}$ and an external rigid body transform $\mathbf{T}$ representing the position of the camera, or projector, in the world coordinate frame.

$$\mathrm{q} = \mathbf{P}\cdot\mathbf{Q} = \begin{pmatrix} \mathbf{KR} & \mathrm{t} \\ \mathbf{0} & 1 \end{pmatrix}\cdot\mathbf{Q} = \begin{pmatrix} \mathbf{M} & -\mathbf{M}^{-1}\mathbf{C} \\ \mathbf{0} & 1 \end{pmatrix}\cdot\mathbf{Q} \tag{1}$$

$$\mathbf{T} = \begin{pmatrix} \mathbf{R} & \mathrm{t} \\ \mathbf{0} & 1 \end{pmatrix} \tag{2}$$

Radial distortion coefficients $\mathrm{d} = \left[k_1, k_2, k_3\right]^T$ are modeled by relating the ideal undistorted image coordinates q to distorted image coordinates $\tilde{\mathrm{q}}$ by

$$\tilde{\mathrm{q}} = \mathbf{K}\cdot L(\tilde{r})\cdot\mathbf{K}^{-1}\cdot\mathrm{q} \tag{3}$$

with

$$L(\tilde{r}) = 1.0 + k_1\cdot\tilde{r}^2 + k_2\cdot\tilde{r}^4 + k_3\cdot\tilde{r}^6 \quad \text{and} \quad \tilde{r} = ||\mathbf{K}^{-1}\tilde{\mathrm{q}}|| \tag{4}$$

where $\tilde{r}$ is the distance from the distorted image point $\tilde{\mathrm{q}}$ to the image center expressed in normalized image coordinates.

The mapping of a point $\mathbf{Q}$, given in world frame coordinates, (e.g. the location of a calibration marker in space) onto its image q in the camera image (e.g. the image location of the calibration marker) is described by the 3×4 linear projection matrix $\mathbf{P}$, also known as camera matrix, see Eq. (1). Determination of the parameters of $\mathbf{P}$ is carried out by a grid of marker features on a planar calibration device in at least three different unknown poses as described in [13]. Radial and tangential distortion coefficients $\mathbf{d}$ are given by a polynomial function $L(\tilde{r})$ of predefined order which is numerically obtained using a Levenberg–Marquardt optimization minimizing the sum of reprojection errors for all calibration