

Reconstruction of three-dimensional surface structure of hard-to-reach objects using prism-based stereoscopic systems

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Abstract. Video endoscopes with stereoscopic prism-based optical systems are widely used for non-destructive testing and geometric measurements of hard-to-reach elements inside complex technical objects. The functionality of the existing devices of this type is limited to a great extent by the capabilities of the embedded software. In this paper, we present our software for the calibration of such systems and the processing of obtained stereoscopic images. It allows to reconstruct and process the whole array of three-dimensional coordinates of the observable object points, to compare it with the reference surfaces and to export the data to other mathematical software.

Keywords: Endoscopy, stereoscopy, three-dimensional imaging, optical system design, geometrical measurements.

1. Introduction

Non-destructive testing (NDT) of inner cavities in industrial objects (engines, steam generators, heat exchangers, etc.) is a mandatory procedure at the stages of its manufacturing, assembling and testing. The quality of the control procedure determines trouble-free operation of these objects [1,2]. At the moment, visual inspection by means of endoscopic equipment is the most common and universal NDT technique for hidden cavities in such objects that do not allow any disassembly [3]. The possibility for delivering an endoscopic probe to the inspected area through a small-diameter holes allows one to effectively solve the main NDT problems, i.e. to visually assess the condition of the surface, to reveal and classify existing flaws and contaminations, and to evaluate their dimensions.

The three-dimensional (3-D) geometrical parameters of the revealed defects may be measured by several methods implemented in modern video endoscopes. The most common method for endoscopic measurements is stereoscopy. It is based on the processing of two images taken from two different viewpoints. Due to small probe diameters (usually about 4–8 mm), the typical implementation of such approach is the utilization of a prism–lens optical system that makes possible to record images taken from different points on a single image sensor [4]. Camera calibration and image processing techniques [5–8] allows one to calculate the 3-D coordinates of object points and make geometrical

measurements. The range and accuracy of the measurements are limited by the accuracy of calibration and conjugate points matching [7,8].

Existing industrial video endoscopes with prism-based stereo adapters are robust tools designed for in-situ NDT of various objects and, therefore, utilize high-quality mechanical, optical and electronic components. In terms of the data processing software, these devices still have a limited functionality which is enough for the most of practical NDT tasks but is insufficient for analytical purposes. Modern closed-source software does not allow to add new specific modules, export raw data (3-D coordinates of points), compare the reconstructed structure with the reference one, estimate measurement accuracy, etc. Hence, the development of universal software for processing of the stereo images obtained by modern industrial video endoscopes with stereo adapters is an important task.

2. Software structure

Our software includes all necessary stages of stereoscopic image processing starting from the geometric calibration of the system to the 3-D data visualization and export. The main software modules are shown in Figure 1. It is important that the software allows to export and correct all utilized and calculated data: calibration images and parameters, disparity map, 3-D point coordinates, etc.

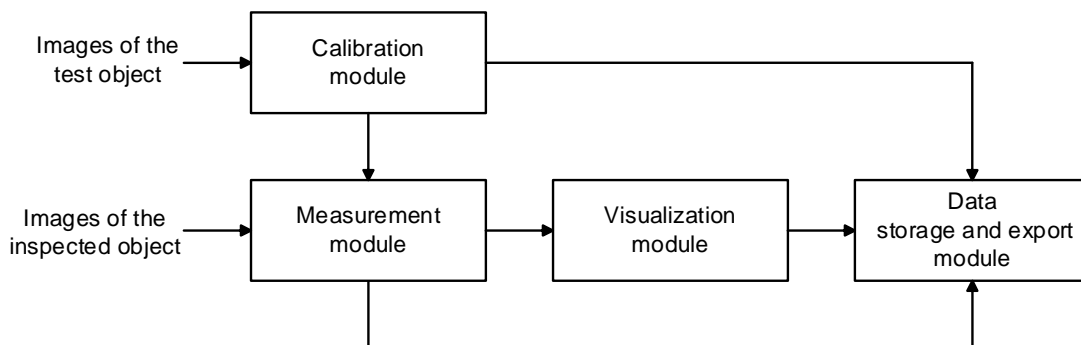


Figure 1. Software structure.

3. Geometric calibration

The aim of the calibration procedure is to determine the value of parameters for the accepted mathematical model of the prism-lens optical system. We consider that we register images of the calibration target with M points in R positions; 3D coordinates of points \mathbf{x}_{tj} , $j = \overline{1, M}$ are known with a certain accuracy in the coordinate system (CS) of the calibration target. The image coordinates $\mathbf{p}_{i,j,k}$ are calculated for each point and each position $k = \overline{1, R}$ as the result of image processing for left and right half of images ($i = 1, 2$). Next, our aim is to find transformations $\mathbf{p}_{i,j,k} = P_i \circ E_i \circ E_k(\mathbf{x}_{tj})$ parameterized by vector \mathbf{k}_i , where E_k stands for the Euclidean mapping from the CS of the calibration target to the world CS. If we introduce the composite vector $\mathbf{x}_{tj} = (\mathbf{x}_{t1}^T, \mathbf{x}_{t2}^T, \dots, \mathbf{x}_{tM}^T)^T$ of all 3D points and the composite vector of all projections $\mathbf{p} = (\mathbf{p}_{1,1,1}^T, \mathbf{p}_{1,2,1}^T, \dots, \mathbf{p}_{1,M,R}^T, \mathbf{p}_{2,1,1}^T, \dots, \mathbf{p}_{2,M,R}^T)^T$, the calibration algorithm K may be written as

$$\hat{\mathbf{k}} = K(\mathbf{x}_t, \mathbf{p}) = \underset{\hat{\mathbf{k}}, \hat{\mathbf{k}}_i}{\operatorname{argmin}} (C(\mathbf{x}_t, \mathbf{p}, \hat{\mathbf{k}}, \hat{\mathbf{k}}_i)), \quad (1)$$

where vector $\hat{\mathbf{k}}$ includes the estimated parameters of the mathematical model. The particular choice of the merit function C depends on the type of the accepted mathematical model [7,8].

We have implemented the calibration algorithms for the pinhole and ray-tracing camera models using non-linear iterative solver for the constrained minimization problem as described in [7,8]. To acquire images for calibration and tests, we used the set of three different-sized plane calibration targets with black and white chessboard pattern (Fig. 2). The distal end of the endoscope was fixed on a mechanical which that allowed adjustable movement along z -axis and rotation around y and z -axis. The axis of the probe was approximately coincident with the z -axis of the stand. Another mechanical

stand was placed in front of the endoscope to mount calibration targets. The calibration sequence included up to 20 images captured at different positions of calibration targets. The developed software allows to locate the chessboard corners on the images automatically, correct or delete points manually if needed, save and load estimated point coordinates and calibration parameters.

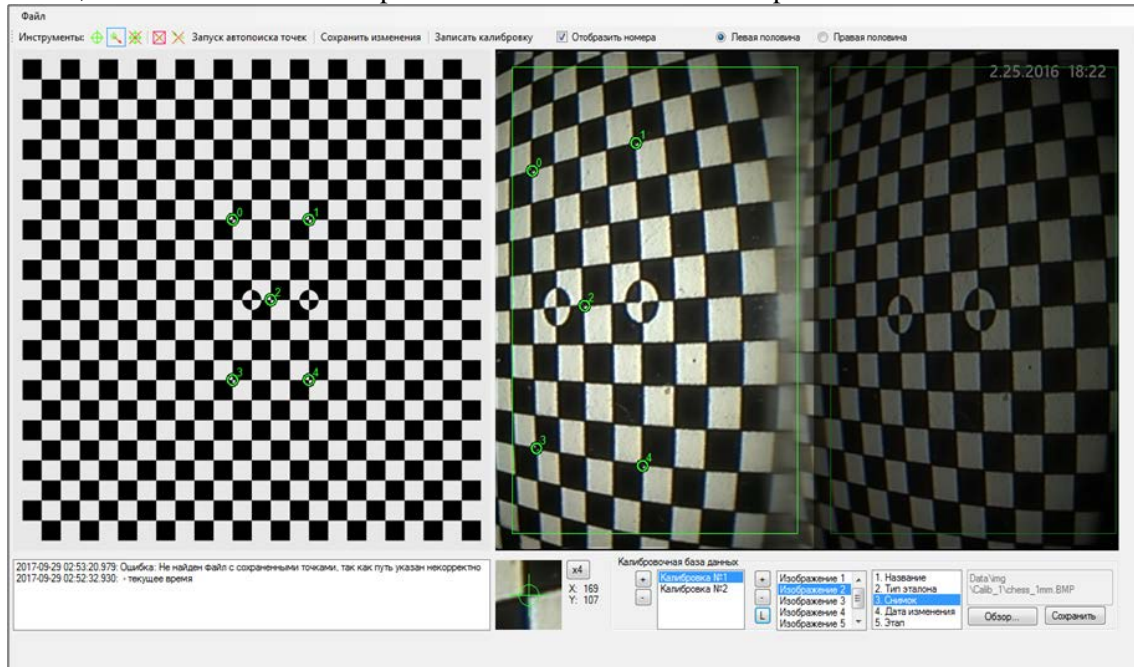


Figure 2. Main window of the calibration module.

4. 3-D geometric measurements

The reconstruction of 3D point coordinates \mathbf{x}_w from 2 projections \mathbf{p}_i may be considered as the ray intersection problem. Because of the uncertainties in coordinates \mathbf{p}_i , these rays are skew, and the triangulation algorithm T is used for the estimation of $\hat{\mathbf{x}}_w$ by minimizing a functional C :

$$\hat{\mathbf{x}}_w = T(\mathbf{p}, \mathbf{k}) = \underset{\hat{\mathbf{x}}_w}{\operatorname{argmin}} (C(\hat{\mathbf{x}}_w, \mathbf{p}, \mathbf{k})), \quad (2)$$

where $\mathbf{p} = (\mathbf{p}_1^T, \mathbf{p}_2^T)^T$. Again, the selection of the appropriate merit function depends on the type of the mathematical model. We can use the cost function based on Mahalanobis distance in the image plane for the pinhole camera model [5] and the function based on point-to-line distance in the 3D object space for the ray-tracing model [7,8]. Thus, in the developed software a full number of image processing algorithms was implemented for both (conventional pinhole and ray tracing) camera models, including calibration, geometrical distortion correction, rectification, matching, etc. Open structure of the software allows to add new modules and change the existing ones.

Fig. 3 shows the main window of the measurement module. Calculation of 3-D points coordinates allows to perform all necessary types of geometric measurements: length, distance from point to plane, perimeter, square, etc., as well as 3-D reconstruction of the inspected surface (Fig. 4). Reconstructed 3D models are saved and stored in ply universal files compatible with 3D modeling programs, such as MeshLab. Moreover, we implemented the alignment of the reconstructed 3-D model and reference (uploaded or selected built-in) structure and calculating the RMS deviation. Currently the database of the typical defects (cavities, cracks, depositions, etc.) is being collected. Depending on the situation, one can upload either color image (split screen mode) or 3-D shape for visual and automated comparison of the inspected object and reference one.



Figure 3. Main window of the measurement module.

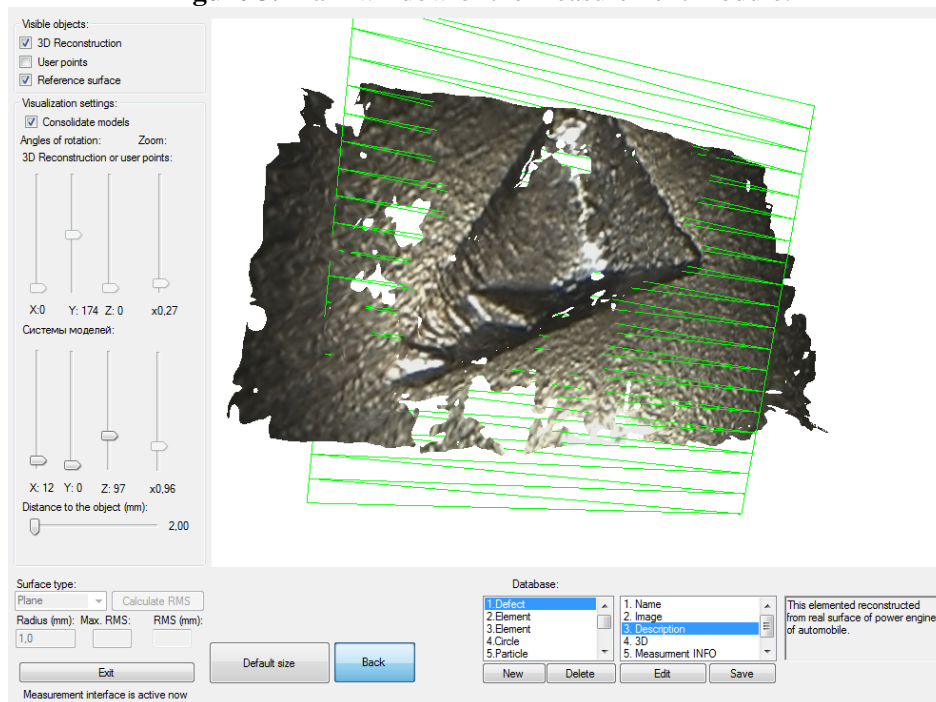


Figure 4. Main window of 3-D visualization module.

Developed software was tested with a few different stereoscopic video endoscopes and multiple images of various test-charts and real objects (turbine blades, pipes, etc.). Experimental results [9] show that implemented ray tracing camera model allows to obtain higher accuracy and wider range of measurements in comparison to the conventional software based on the pinhole models.

5. Conclusion

In this paper, we presented a universal and multi-functional software for processing the images obtained by modern video endoscopes equipped with stereo adapters. It allows to perform not only mandatory procedures (calibration, measurements) but also to widen the functionality of the existing

software packages (extended 3-D visualization and processing, data export options, etc.). The software provides the control of the hard-to-reach objects shape and the analysis of its surface defects in many NDT applications. It may be useful for the improvement of the existing prism-based video endoscopic imagers in terms of the measurement range and accuracy as well as for the development of the new small-size tools for remote visual inspection, especially for the important industrial tasks where high precision of defect characterization is crucial.

6. Acknowledgments

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7. References

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