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Structured light scanning method in the detection of workpiece defects

Streszczenie. *Artykuł stanowi opis propozycji zastosowania skanera wykorzystującego światło strukturalne w celu identyfikacji wad detali poddawanych obróbce. Artykuł stanowi część prac związanych z opracowaniem linii do automatycznej identyfikacji wad na elementach obrabianych. W artykule dokonano uzasadnienia wyboru metody skanowania oraz wyniki pomiarów przy użyciu skanerów światła strukturalnego określające możliwości wykorzystania ich w wizyjnej detekcji wad.*

Abstract. *The article is a description of the feature extraction method, used in the classification of defects in workpieces undergoing a process. The publication is a part of the work related to the development of a line for automatic identification of defects on workpieces. It describes a method of extracting features, in which voxelization results were used to obtain the parameters of characteristic defects. The results are illustrated with examples. (**Metoda skanowania z użyciem światła strukturalnego w procesie identyfikacji wad detali)***

Słowa kluczowe: detekcja wad, systemy wizyjne, światło strukturalne, proces skanowania, skanery światła strukturalnego
Keywords: defect detection, vision systems, structure light, scanning process, structure light scanner

Introduction

This article is related to a research and development project aimed at developing an innovative solution in the form of a line (production and technological) for the automatic identification of defects on workpieces subjected to blasting and is a stage in the development of a vision-based defect detection technology, which is one part of the production process. The vision system aims to visualize the physical characteristics of the analyzed component for measurement and quality control purposes [1], [2]. The data collected by the system enable to obtain precise information on the location of the defect and are considered as the basis for selecting the method of defect removal and for proceeding to the next stage of the process. It is assumed that the system will consist of vision equipment and an image acquisition and processing system, combining both acquisition, image processing and software, to automate the control, measurement and production process steps. The choice of scanning technology is crucial in the process of developing a 3D image of a component with defects, which will be subjected to an assessment of the degree of deformation compared to the template component [2], [3]. This paper presents and justifies the choice of a structural light scanning method. The results of measurements made using structured light scanners determine the possibilities for their use in vision-based defect detection. Conclusions and a summary of the research on the use of other vision methods (vision sensors, laser scanners) and photogrammetric methods can be found in the authors' previous work on seeking solutions to the same problem. The technologies analyzed in the research preceding this paper were related to: laser profilometers, line cameras, handheld 3D scanners [1], and photogrammetry using various industrial cameras and sensors [3].

Technology

Devices using the technology described below could accurately be called pattern-emitting light systems [4], but are more commonly referred to as structured light systems in the professional literature ([3],[7]). This name also functions among manufacturers of this type of 3D scanners (Keyence, Lenso, Evatronix, SmatTech), therefore, the authors have chosen to use it.

Structured light scanning is widely used primarily in computer graphics [7], e.g. for so-called 'hand tracking' in virtual reality systems [8], imaging of the underwater world [9], positioning [5], but also in completely different fields of technology, e.g. in measurements of welding deformations [6] or wear analysis of mining link chains [10] and many others [7].

Structured lighting systems work in a similar way to stereo vision systems, with one camera being replaced by a projector [7] (see fig. 1). A measurement method involving the spread of geometric lines and patterns on the object under examination and the analysis of the deformation of the displayed patterns and, based on this, the generation of the object's 3D structure is used. The scanning process proceeds as follows: the pattern is, for example, a repeatable square set of stripes that have the same intensity $I_p(x,y)$ along each vertical line, and the intensity along the horizontal line is defined as [8]:

(1) $$X_l(x,y) = X(x,y) - nT,$$

(2) $$I_p = 255\left[1 - \left(\frac{X_l(x,y)}{T/2}\right)^2\right],$$

where:

T – length of the recurrence distance of each strip,
n – bar number,
$X_l(x,y)$ –point position (x,y) from the range [-$T/2$, $T/2$],
$X(x,y)$ – absolute position of the point, which is the encoding value stored in the pattern.

The first step of the scanning is equipment calibration through which the camera and projector parameters are obtained. The calibration allows to obtain the projection relationship between the 3D point $X_W = [X_w, Y_w, Z_w, 1]^T$ with the corresponding image point (camera) $x_c = [u_c, v_c, 1]^T$ and the projection point (projector) $x_p = [u_p, v_p, 1]^T$ defined as [8]:

(3) $$x_c = K_c\lfloor R_c\rfloor, \lfloor T_c\rfloor X_W,$$

(4) $$x_p = K_p\lfloor R_p\rfloor, \lfloor T_c\rfloor X_W,$$

where: K_c, K_p – camera and projector internal parameter matrices, R_c, R_p - camera and projector rotation matrices, T_c, T_p - camera and projector translation vectors.

After the calibration process, these matrices have the form:

(5) $$K_c = \begin{bmatrix} {f_c}/{du_c} & 0 & u0_c \\ 0 & {f_c}/{du_v} & v0_c \\ 0 & 0 & 1 \end{bmatrix},$$

(6) $$K_p = \begin{bmatrix} {f_p}/{du_p} & 0 & u0_p \\ 0 & {f_c}/{du_p} & v0_p \\ 0 & 0 & 1 \end{bmatrix},$$

(7) $$R_c = \begin{bmatrix} R_c^{11} & R_c^{12} & R_c^{13} \\ R_c^{21} & R_c^{22} & R_c^{23} \\ R_c^{31} & R_c^{32} & R_c^{33} \end{bmatrix},$$

(8) $$R_p = \begin{bmatrix} R_p^{11} & R_p^{12} & R_p^{13} \\ R_p^{21} & R_p^{22} & R_p^{23} \\ R_p^{31} & R_p^{32} & R_p^{33} \end{bmatrix},$$

(0) $$T_c = \begin{bmatrix} T_c^1 \\ T_c^2 \\ T_c^3 \end{bmatrix},$$

()10) $$T_p = \begin{bmatrix} T_p^1 \\ T_p^2 \\ T_p^3 \end{bmatrix},$$

where:
f_c, f_p – camera and projector focal lengths,
du_c, dv_c – camera horizontal and vertical pixel size,
du_p, dv_p - projector horizontal and vertical pixel size,
$(u0_c, v0_c)$, $(u0_p, v0_p)$ – camera and projector base points.
Next, the source (e.g. an LCD projector) emits light through a pattern matrix onto the object under study, and the vision sensor (or several cameras that are offset from the projector) examines the shape of the reflected light pattern projected onto the object and calculates the distance from all points in the field of view [5], [6]. Pattern decoding provides information about the position of the corresponding points between the pixels in the captured image and their equivalents in the output pattern matrix. For a pattern consisting of only vertical bars for a pixel (u_v, v_c) in the captured image (camera), the corresponding bar position in the pattern of the decoding process can be obtained. 3D reconstruction is performed based on the collinearity equation. Distortions in the light bands caused by height differences are converted to height using trigonometric triangulation.

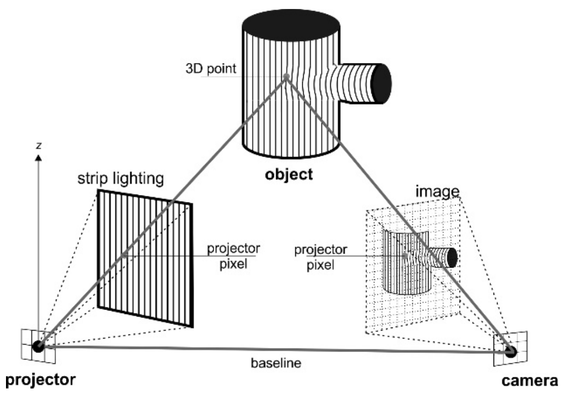


Fig. 1. Structured light scanning method
Fig. 2.

Structured light can be white, blue or green, and the pattern is most often stripes or a matrix of dots. In many solutions, the illuminator emits structured light from several light sources, which allows to reduce distortion and increase measurement accuracy. The use of high-precision optical sensors enables colour recognition.

Measurements

The first experiment involved scanning a test sample (fig. 3) with several devices, differing in the type of light source emitted by the LED projectors (Table 1). In all cases, the scanning result was a point cloud and visualisation of the sanitised element.

Fig. 3. Model of the test sample

Tab. 1. Scanner types

	scanner 1	**scanner 3**	**scanner 4**
Type of LED light	blue	white	green
Number and type of cameras	2x7 Mpix	no data	2x3,1 Mpix
Scanning accuracy *)	9 μm	no data	15μm
Measurement time	2 min	2 min	4 min

*) according to standard: DE I/VDE2634 Part 2,4.1 Ps

In all cases where structured light scanners are used, it can be concluded that the advantages of this technique are speed and high accuracy, while glossy and black surfaces pose a problem, due to the difficulty in analyzing the incident light. Given the obtained results, it can be stated that the blue-light systems performed most effectively with the imaging of the defects applied to the component under examination (fig. 4, fig. 5, fig. 6). The obtained parameters and access to data should guarantee the possibility of obtaining a 3D model of the object with an accuracy of 0.1 mm in approximately 2 minutes. Testing performed with the white light scanner was not satisfactory, the biggest drawback being the complicated calibration of the head with the illuminators and camera, as well as the low measurement depth range. Measurements of the test sample with the structured green light gave results that are superior to the white light methods, while the disadvantage of this solution was the long scanning time and the need to matt the object.

Further scanning with structured light tests involved visualizing objects with other shapes and glossy surfaces. Additional tests were carried out with scanner 1, emitting blue light. In both cases of the scanned samples, the shiny surfaces of the components were a major difficulty, making analysis of the incident light difficult. It was necessary to spray coat the smooth elements with a self-disappearing substance (after 3h) to matt their surfaces.

a)

b)

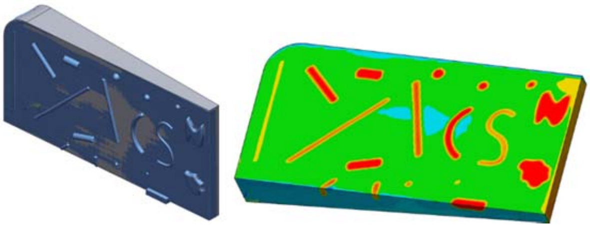


Fig. 4. Testing with blue structured light (a) test stand (b) selected test results

a)

b)

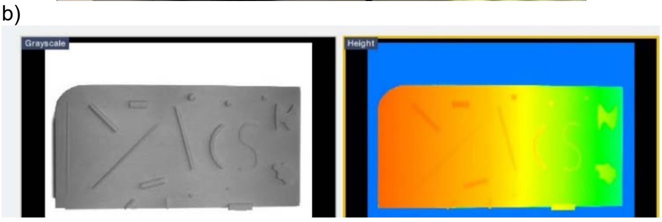
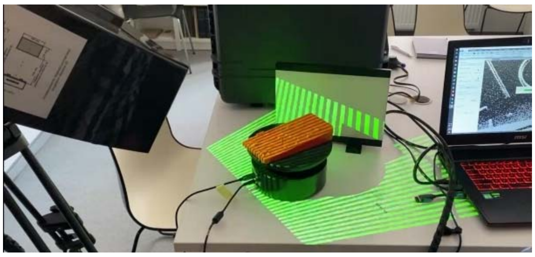


Fig. 5. Testing with white structured light (a) test stand (b) selected test results

a)



b)

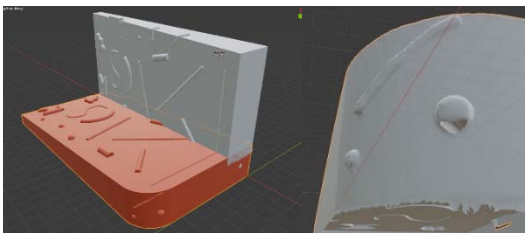


Fig. 6. Testing with green structured light (a) test stand (b) selected test results

The results for two additional objects, a cube and a roller, are presented below. A series of tests (scans) were carried out on an element in the form of a cube with defects (fig. 7). A naturally shiny element and an element coated with a mattifying substance were subjected to the scanning test. Only in the latter case, satisfactory imaging results were obtained.

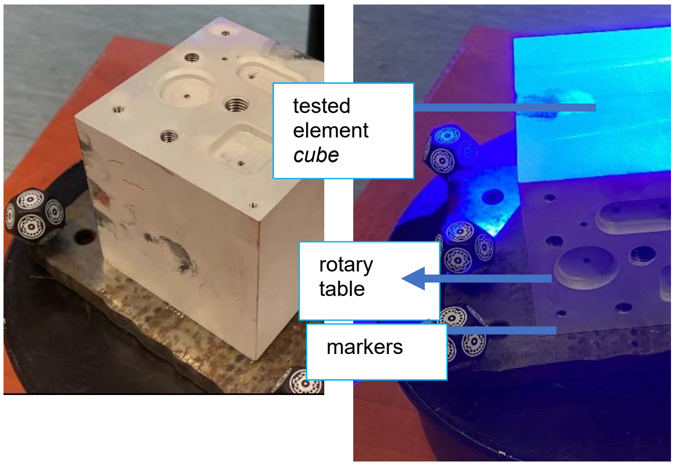


Fig. 7. Scanning the cube

Additional elements in the form of rubber rings were added during the measurement cycle. The test results are presented in fig. 8.

a) b)

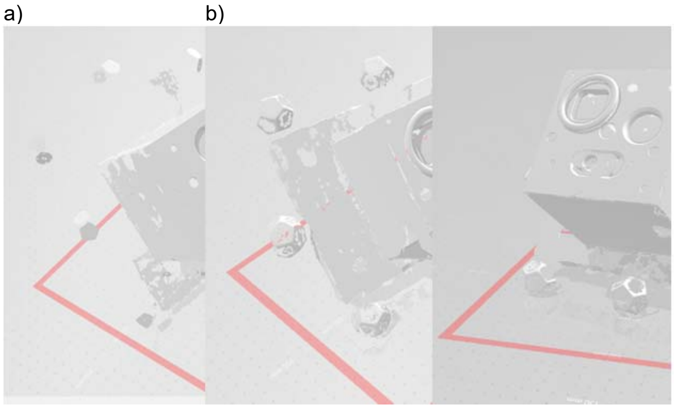


Fig. 8. Scanning results of the cube a) scan result without markers b) scan result of the cube with markers and additional normals

In the next cycle, a series of tests (scans) was performed on an element in the form of a roller with defects (in fig. 9). Also, additional elements in the form of rubber rollers were introduced during the measurement cycle (results in fig. 10). The tested device met the requirements for scanning speed and form of data recording as well as acquisition (in the form of .stl files). The architecture of the proposed system involves reconstructing the 3D model of the object from the raw data and providing information on the location of the identified defects. The coordinate system of the stored image is determined with respect to the placed markers and can thus be transferred to the next stages of the process. Defects can arise from potential errors in image composition when scanning elements with smooth surfaces causing reflections and making analysis of the image much more difficult.

During the scanning process, possible inaccuracies causing localized deficiencies in the given grid of points describing the object must be assumed. Therefore, in the final industrial solution, the use of a curtain with a matting agent before the item enters the inspection chamber is recommended.

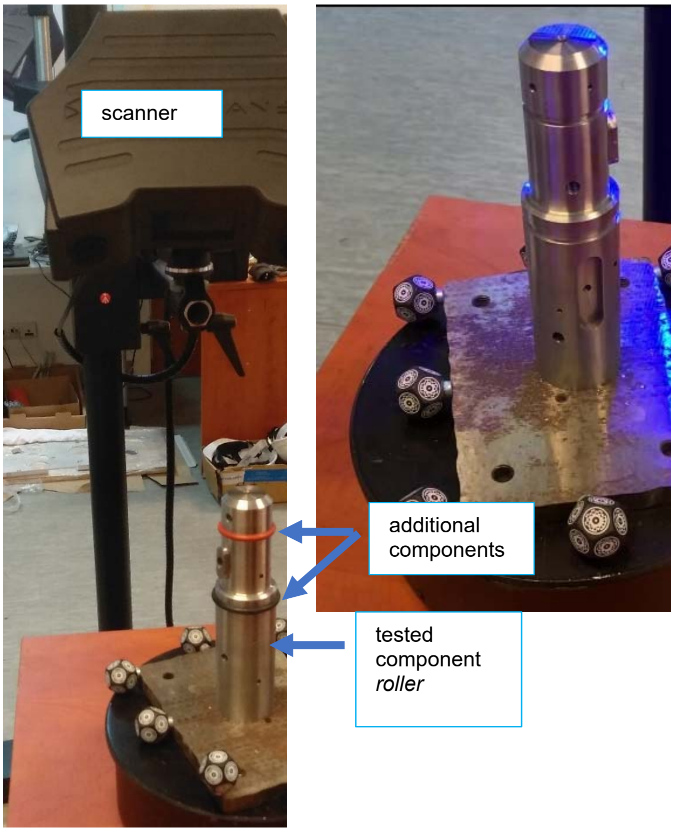


Fig. 9. Scanning the *roller*

a) b)

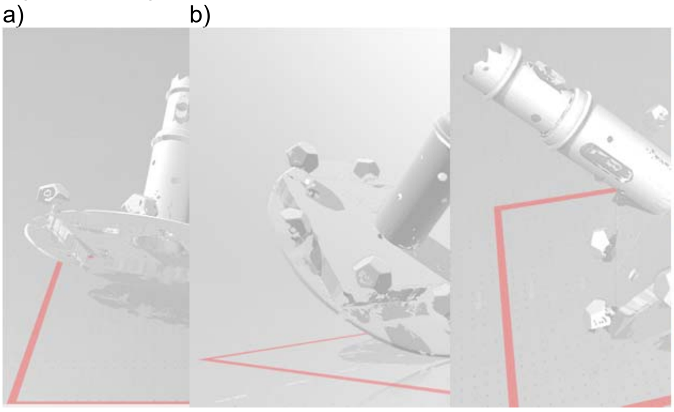


Fig. 10. Scanning results of a roller a) scanning result without markers b) scanning result of a cube with markers and additional normals

However, the use of such an agent strongly depends on the shape and material of the object under test. During the conducted test, a cube was matted, while a roller did not require this operation, with a triple exposure to scanning.

Conclusions

Based on current tests and a previous analysis of available technologies summarized in the article [1], a method for scanning 3D objects was selected. The best results are obtained using structured light cameras, as they enable to achieve the assumed 0.1 mm accuracy of object reproduction. As for the remaining technologies, the mapping does not offer such possibilities or require much more complex calculations the time of which significantly exceeds the assumed few minutes for computer processing of the data. In the opinion of the team, structured light scanners are the most appropriate solution, as the built-in frameworks make it possible to obtain a point cloud or mesh model with satisfactory accuracy in a short period of time. A drawback, however, is the possibility of errors when registering light reflections from smooth and shiny surfaces, which can be encountered on scanned objects, as they will ultimately be made of metal. This problem is solved by coating the scanned objects with a matting agent.

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