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DIFFERENTIAL DIGITAL HOLOGRAPHY IN QUALITY CONTROL

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Original scientific paper

This paper describes a method of differential digital holography applicable in quality control for some manufacturing processes. The proposed method is able to differentiate 3D objects without production defects and similar 3D objects with production defects. Holograms of all objects are created using off-axis laboratory setup. Computer is used to compare holograms or difference holograms and determine whether the manufactured object has some defect or no defect. Production defects can be in the form of pattern errors or in the form of surface bumps. A model of production setup for implementation in manufacturing processes is proposed.

Keywords: *digital hologram, defect detection, product quality control*

Diferencijalna digitalna holografija u kontroli kvalitete

Izvorni znanstveni članak

U radu se opisuje metoda diferencijalne digitalne holografije koju je moguće primijeniti u kontroli kvalitete u nekim proizvodnim procesima. Predložena metoda može razlikovati 3D objekte bez oštećenja i iste objekte ali s nekim oštećenjem koje se pojavilo tijekom proizvodnje. Snimaju se hologrami svih objekata na vanosnom laboratorijskom postavu. Računalo se koristi za usporedbu holograma ili razlike holograma i određivanje ima li proizvedeni objekt neko oštećenje ili grešku. Pogreške mogu biti u vidu pogrešaka u teksturi na površini proizvoda ili u obliku nepravilnog reljefa proizvoda. Predložen je model postava za proizvodnju u industrijskim procesima.

Ključne riječi: *digitalni hologram, detekcija pogrešaka, kontrola kvalitete proizvoda*

1
Introduction
Uvod

There are some methods and algorithms that analyze pictures of manufactured objects and grade them in classes according to size and number of detectable defects [1-9]. One significant drawback of those methods is the inability to detect surface bumps, i.e. 3D defects. Only pattern defects can be detected by analyzing 2D picture of a 3D object.

Our goal was to design a defect detection method with ability to detect defects both in 2D and 3D objects. One method to record a 3D object with all information is to use stereoscopic vision like human eyes. For a stereoscopic object recording two sensors (or cameras) would be necessary. Considering high sensor price cheaper experimental setup was also one of the goals. Laser sources can be bought in the price range from $20 to $50 US.

Relying on the hologram's feature to record 3D information in the form of 2D picture, a new method was developed. Computer simulation was performed to test the method results [10]. The proposed method is able to detect surface defects on recorded 2D picture (hologram) of a 3D object. One significant drawback of holography in the proposed method is that only the illuminated side of a 3D object is recorded in the hologram. Where the recorded object is almost flat, like a ceramic tile, only one side has to be illuminated to make a hologram of that surface. In this way the mentioned drawback has no impact in quality control. Some mathematical methods will be mentioned to compare experimental results.

Two laboratory equipment setups will be mentioned and explained. Equipment availability imposed constrains to use only one of laboratory equipment setups. Differential digital holography process will be explained in details. Step-by-step guideline will be provided. Possible industrial applications are mentioned in earlier papers [11-13].

2
Digital holography
Digitalna holografija

The concept of digital holography refers to an approach where holograms are recorded using discrete electronic components rather than a photo-film. The recorded digital holograms are 'ready to use' and no additional handling is necessary, unlike the holograms recorded on a photo-film. Discrete electronic component used to record holograms is CCD (Coupled Charged Device) sensor or more sensitive and faster CMOS (Complement Metal Oxide Semiconductor) sensor.

2.1
CCD/CMOS sensor
CCD/CMOS sensor

CCD/CMOS sensor consists of two areas: a photo-active area, used to acquire images and a transmission area, made of shift registers. Image is propagated through one or more optical lens (used only in acquiring photographs, NOT holograms) and projected to two-dimensional array of capacitors (photo-active area) causing accumulative effect of electric charge in the capacitors which is proportional to the light intensity in that location. One-dimensional array (line) is used in line cameras and can record only small part of image (one line). Two-dimensional arrays are used in photo and video cameras to record 2D picture that represents 3D scene propagated through optical lens and projected to sensor array. There are variations in sensor implementation, both for CCD and for CMOS sensors. Commonly used implementations are full-frame and interline.

In full-frame implementation the entire sensor area is active and there is no electronic shutter. This implementation requires additional mechanical shutter or the recorded image will be blurred after the sensor is covered and light intensities detected.

Frame-transfer sensors have half of the silicone area covered with opaque mask (aluminium). Image is transferred from illuminated area to opaque area very fast. Recorded image is read from opaque area while new image can be integrated or projected to active area. This implementation does not require mechanical shutter and this was common architecture in early cameras. Significant drawback of this implementation is a requirement of sensors that have twice larger surface than full-frame implementation which causes them to be more expensive.

Interline architecture expands frame-transfer concept by one step and masks odd rows of sensor array for storage. In devices with interline architecture there is a shift from picture area to storage area by one pixel. Shuttering speed can be less than one microsecond without blur. This feature has one major drawback: picture area is covered with opaque bands which reduces effective sensor area to 50 %.
Higher CCD/CMOS sensor resolution and sensitivity is the reason why digital technology is rapidly growing for usage in hologram recording. Some of the advantages of digital technology are:

- very fast image (hologram) recording,
- fast transfer of recorded holograms from sensor to PC,
- possibility of recording great number of holograms because no other recording materials are necessary (recording can be repeated until the recorded hologram quality is satisfactory),
- absence of chemicals for photograph treatment (there is no limit to how many holograms one can record because there is no limit to the numbers of photo-films).

2.2
Digital hologram
Digitalni hologram

Hologram is an interference pattern recorded on the surface of the sensor. The interference pattern originates from two sources: object wave and reference wave. Recorded hologram contains both amplitude and phase information about the object from the scene. One can observe the recorded object by reconstruction with different perspectives and depths. Optically recorded hologram can be reconstructed by illuminating interference pattern photo-film with original reference wave. In digital holography mathematical calculation that simulates optical illumination process of hologram with reference wave is applied on digital hologram to produce amplitude and phase of the recorded scene. Reconstructed object on the scene can be further analyzed and/or processed. The process is called numerical reconstruction. Digital holograms can be optically reconstructed by spatial light modulators and original reference wave.

2.3
Optical and digital holography comparison
Usporedba optičkog i digitalnog holograma

Standard photography uses a system of lenses to focus dispersed light from the scene on photo-film or CCD/CMOS sensor resulting in a focused picture of the recorded scene. The illumination used to record the scene is incoherent which means that light wave consists of many different phases and wavelengths (sunlight for example). Light is reflected from the object on the scene and the reflected wave traverses to the recording medium. The laser beam used to record digital holograms is divided into two waves: object wave and reference wave. Object wave, which has to be broadened enough to illuminate the whole recorded object, reflects from the object and propagates to the recording medium. Reference wave traverses unchanged from the light source to the recording medium where it interferes with the object wave. The recorded interference pattern is called interferogram or hologram. To ensure the interference process, light source must be coherent. Both the process of image recording and that of hologram recording are shown in Figures 1 and 2.

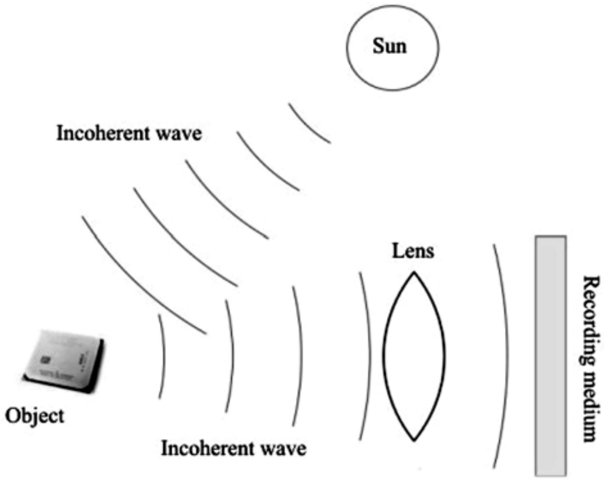

Figure 1 *Photograph recording setup*
Slika 1. *Snimanje fotografije*

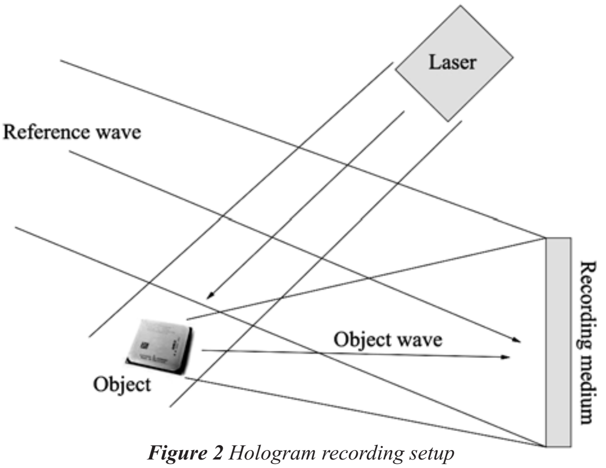

Figure 2 *Hologram recording setup*
Slika 2. *Snimanje holograma*

2.4
Laboratory setups for digital hologram recording
Laboratorijski postavi za snimanje holograma

There are two setups for a hologram recording process. The first one is in-line setup and it is very similar to the original Gábor setup. Reference wave traverses the same way and has the same direction and incident angle to the recording medium as object wave. Unlike the setup suggested by Gábor [14,15], there is a way to split light source beam (wave) into two identical beams (waves)of half the intensities of original light source beam. One of the waves illuminates the object thus becoming the object wave. The second wave traverses unchanged to the recording medium. One beam splitter is used to split light source beam and the other beam splitter is used to realign the object and the reference beam so they have the same incident angle to the recording medium. In-line setup is shown in Fig. 3.

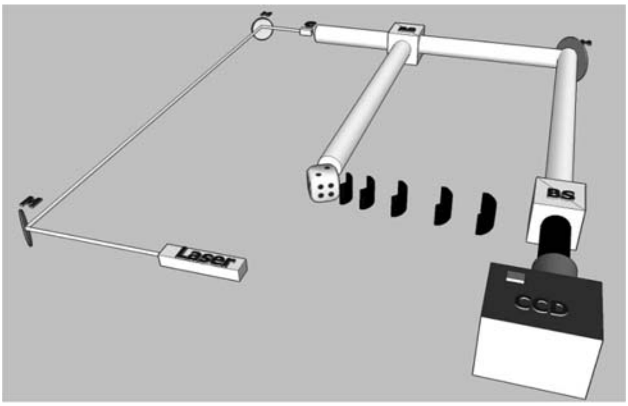

Figure 3 *In-line setup*
Slika 3. *Osni postav*

In off-axis setup object wave and reference wave do not have the same incident angle to the recording medium. This setup requires only one beam splitter used to split light source beam. There is one major drawback in off-axis holography – the recorded object has to be placed at a relatively large distance from the recording sensor. For example, using sensor with 2048×2048 pixels and 7,4 μm sensor dot size, with laser light source of wavelength 632 nm, the object with 10 mm^2 has to be placed at a minimum distance of 2516 mm from the sensor. Minimal distance $d_{\text{off-axis}}$ between object and sensor is expressed with

$$d_{\text{off-axis}} = \frac{\delta\xi(\Delta X + 4\Delta O)}{\lambda} \tag{1}$$

where $\delta\xi$ is pixel spatial resolution calculated as the ratio between sensor length (ΔX) and number of sensor pixels along the same axis, ΔO is size of object and λ is light source wavelength. Off-axis setup is shown in Fig. 4.

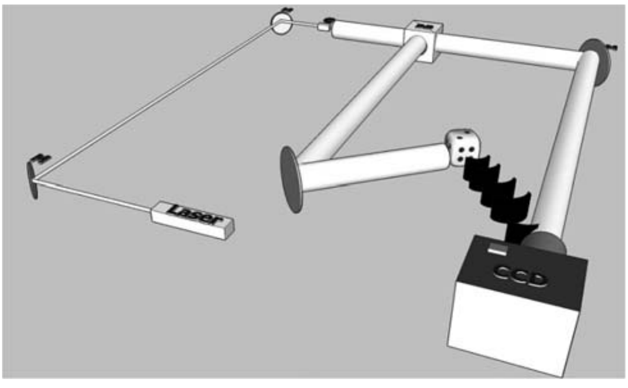

Figure 4 *Off-axis setup*
Slika 4. *Vanosni postav*

2.5
Mathematical description of holograms
Matematički opis holograma

To be able to understand what the hologram is composed of mathematical equations will be used to describe what is recorded on the sensor. Reference wave can be formulated as:

$$R_{\Delta\Phi}(x,y) = A_{R_{\Delta\Phi}}(x,y)\mathrm{e}^{i\left[\Phi_{R_{\Delta\Phi}}(x,y)+\Delta\Phi\right]}, \tag{2}$$

where $\Delta\Phi$ is arbitrary phase shift between reference wave and object wave. Object wave can be formulated as:

$$O(x,y) = A_O(x,y)\mathrm{e}^{i[\Phi_O(x,y)]}. \tag{3}$$

Expression $A(x,y)$ is the wave amplitude and $\Phi(x,y)$ is the wave spatial phase. Interference pattern $H(x,y)$ created on the sensor surface is superposition of reference wave and object wave.

$$H(x,y) = O(x,y) + R_{\Delta\Phi}(x,y). \tag{4}$$

Sensor can only detect and record the light intensity. In the process of recording the object wave sensor would detect and store as data only the intensity of the object wave represented by the squared amplitude of the same wave - $A_O^2(x,y)$. Reference wave intensity is recorded as $A_{R_{\Delta\Phi}}^2(x,y)$. When those two expressions are added the result is given by $A_O^2(x,y) + A_{R_{\Delta\Phi}}^2(x,y)$ which represents the image consisting of information just about object wave – squared amplitude. This process has information loss and the resulting object image would not be focused. Since CCD/CMOS sensor can only record intensities the process of recording digital holograms with more information about object wave than just intensities will be explained. In the object wave and the reference wave interference process at the sensor surface the information that is recorded can be expressed with

$$H_{\Delta\Phi}(x,y) = \left\| O(x,y,0) + R_{\Delta\Phi}(x,y,0) \right\|^2. \tag{5}$$

Intensities are recorded after complex object and reference wave interference. After expanding expression for recorded hologram the result is given with

$$\begin{aligned} I(x,y) = O^2(x,y) + R_{\Delta\Phi}^2(x,y) + O^*(x,y) \cdot \\ \cdot R_{\Delta\Phi}(x,y) + O(x,y)R_{\Delta\Phi}^*(x,y), \end{aligned} \tag{6}$$

where * is complex conjugate. This representation simplifies the explanation of digital hologram components. Expressions $O^2(x,y)$ and $R_{\Delta\Phi}^2(x,y)$ are DC offset and they are source of noise in digital hologram. Real picture is represented by expression given by $O^*(x,y)R_{\Delta\Phi}(x,y)$ and virtual picture is represented by $O(x,y)R_{\Delta\Phi}^*(x,y)$. Real and virtual images combined represent a twin image. Only one of the images is necessary for the process of reconstruction. Only one part of the twin image multiplied by the reference wave (or complex conjugate reference wave) will propagate the object wave. Reconstruction of the reference wave propagation from hologram is performed by numerical calculation. Performing numerical reconstruction prior to the virtual image removal process can result in errors in the reconstructed image.

2.6
Error removing and twin image problem
Otklanjanje izvora pogrešaka i problem slika blizanaca

Two error sources are identified as offsets to which the object and the reference wave contribute with their amplitudes (intensities) O^2 and $R^2_{\Delta\Phi}$. Those errors dominate in the domain of low frequencies band of the hologram interference lines. There are two possible methods to suppress or remove the offsets. The first method includes separate recording of object and reference wave and the whole hologram too. After the recording process unwanted offsets (object and reference wave) can be subtracted from hologram resulting in a twin image without errors (offsets). To perform this method the object that is recorded has to be motionless until all tree images are recorded. Thus the number of industrial processes where this method can be applied is narrowed. Fast digital cameras can overcome this problem. The other method is the application of filter which will remove the unwanted low frequencies where errors are located.

Twin image does not represent a problem in the proposed method because two digital holograms, both recorded from the same object, are subtracted. The presence of twin images amplifies the difference between two similar holograms.

2.7
Advantages and disadvantages of in-line and off-axis setups
Prednosti i nedostaci osnog i vanosnog postava

In-line hologram advantages:
- smaller distance between object and sensor
- higher sensor efficiency.

In-line hologram disadvantages:
- real and virtual images are in the same position in reconstructed image
- mathematical calculation is necessary for twin image removing process.

Off-axis hologram advantages:
- real and virtual image are not in the same position in the reconstructed image.

Off-axis hologram disadvantages:
- distance between object and sensor has to be four times greater than in in-line holography
- lower sensor efficiency.

3
Differential Digital Holography
Diferencijalna digitalna holografija

This section proposes a new method able to detect errors in third dimension of the recorded object. The name of the method suggests that the holograms of objects are used. The proposed method originates as one possible upgrade to existing methods for surface pattern error detection. Besides pattern error detection there is a requirement to detect surface flaws. Those errors or flaws can be:
- erratic thickness of surface layer,
- impurities in surface layer that can distort surface in the form of bulges,
- scratches,
- cracks in material.

Laboratory setup for off-axis digital hologram recording process is shown in Fig. 5.

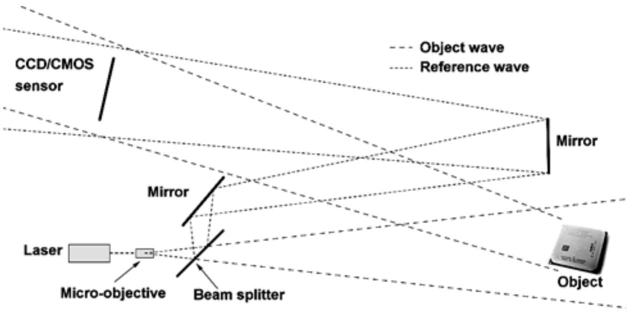

Figure 5 *Off-axis laboratory setup for hologram recording*
Slika 5. *Laboratorijski postav za snimanje vanosnih holograma*

In digital hologram recording process where 3D object is recorded the format of recorded hologram depends on the used CCD/CMOS sensor, or in this experiment on digital camera. The sensor used in experiment was part of the digital camera and the recorded pictures are in RAW picture format. Pictures in RAW format do not support any kind of compression which is one of major demands in the hologram recording process. Any kind of image compressing introduces loss of some data. Standard image formats like JPG or GIF are not suitable for storing holograms.

3.1
Experimental setup equipment parts
Dijelovi laboratorijskog postava

Experimental setup equipment for digital hologram recording consists of:
- coherent light source – green laser – 532 nm wavelength, 50 mW output power
- micro-objective (two lens system - 20/0,40, 160/0,17) – length: 5 mm, diameter: 23 mm
- beam-splitter – 30 × 50 mm
- mirrors
- squared – 30 × 30 mm, flat
- round – 80 mm diameter, flat
- mounts for equipment (laser, mirrors, beam-splitter, micro-objective)
- recording object (heart-shaped ceramic jewelry box)
- digital camera with sensor (CMOS)
- light absorbing black paper – standard A3 size.

Instead of standalone sensor digital camera with CMOS sensor was used in experiment. In that way additional electronic circuitry assembling for sensor-computer communication was evaded. Digital camera used in experiment was Canon EOS 30D with CMOS sensor of 8 Mpix (somewhat over eight million sensor pixels) with USB interface for communication with computer and Compact Flash memory card for images storage. Canon EOS 30D is DSLR camera (Digital Single-Lens Reflex). Photo lenses can be detached from the body of camera and holograms can be recorded instead of plain photographs.

3.2
Off-axis setup modification
Modifikacije vanosnog postava

Prior to the digital hologram recording process some modifications on off-axis setup shown in Fig. 5 had to be made. First step is the digital hologram recording process on unmodified off-axis setup shown in Fig. 5. In the error removing process first step is blocking the reference wave to reach the sensor and recording only the object wave intensities $O^2(x,y)$. It is performed by placing opaque obstacle in the reference wave way. First setup modification is shown in Fig. 6.

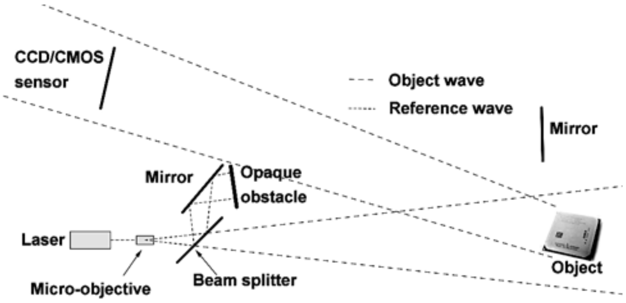

Figure 6 *Modified off-axis setup for object wave intensities recording*
Slika 6. *Modificirani vanosni postav za snimanje intenziteta objektnog vala*

Last step in the recording process is eliminating the second source of errors designated as the object wave intensities and recording only the reference wave intensities expressed with $R^2_{\Delta\Phi}(x,y)$. It is the object wave that has to be blocked with opaque obstacle. Fig. 7 shows the modified setup for reference wave intensities recording.

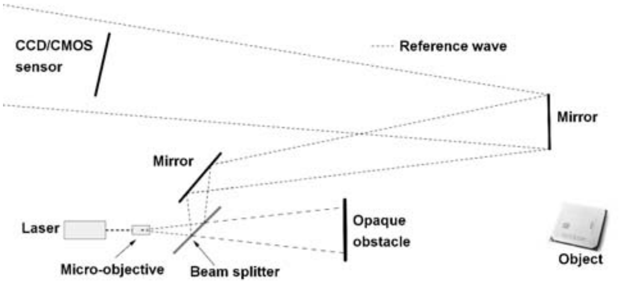

Figure 7 *Modified off-axis setup for reference wave intensities recording*
Slika 7. *Modificirani vanosni postav za snimanje intenziteta referentnog vala*

After the hologram (first step), object wave (second step) and reference wave (third step) recording process some calculations have to be made. Object wave intensities are subtracted from hologram intensities and then reference wave intensities are subtracted from hologram intensities too. The result of subtracting will be a twin image digital hologram without errors. All recorded images (hologram, object wave intensities and reference wave intensities) have to be the same in size so the calculations can be performed. The calculation algorithm for the image intensities subtracting is performed according to

$$I_H(x,y) = I_{H\mathrm{err}}(x,y) - I_O(x,y) - I_R(x,y), \tag{7}$$

where $I_H(x,y)$ is the twin image hologram intensities without errors, $I_{H\mathrm{err}}(x,y)$ is the hologram intensities with error (recorded hologram), $I_O(x,y)$ is the object wave intensities and $I_R(x,y)$ is the reference wave intensities.

3.3
Additional steps in performing DDH
Dodatni koraci u izvođenju DDH metode

DDH method is performed in several steps. Before the digital hologram recording process it is necessary to select a reference object without visible defects. This process of reference object selection is necessary because the holograms of all other recorded objects will be compared to the hologram of the reference object. Detailed description of the steps in DDH method is as follows:

1. reference object selection
2. reference object digital hologram recording
    a. interference pattern of object wave and reference wave recording
    b. object wave intensities recording
    c. reference wave intensities recording
    d. twin image digital hologram calculation
3. other objects digital hologram recording with all four steps as in 2nd step (a, b, c, d)
4. reference object digital hologram and any other object digital hologram difference calculation
5. result analysis.

The DDH method first step is performed only once and it has to be performed by a human to select a reference object. All other steps can be performed in automated process and calculations are performed on computer.

4
Experiment
Pokus

After the placement of equipment according to Fig. 5 the process of digital holograms recording could take place as described earlier. All recorded holograms had to be transferred to the computer for processing. Pictures were in RAW format (CR2 file extension) so they had to be changed first to the TIFF and then to the BMP picture format. The BMP picture format is best suited for mathematical calculations because the calculating algorithm can get the RGB values from the picture very easily and no compression is applied to the recorded hologram.

The object used for experiment was a white ceramic box for jewelry shown in Fig. 8.

Figure 8 *Object used in experiment*
Slika 8. *Objekt upotrebljen u eksperimentu*

Digital hologram recorded from the object shown in Fig. 8 was a reference hologram.

Artificial defects were made from wrinkled black paper. The first defect was on the right side of the object as shown in Fig. 9, and the second defect was on the left side of the object as shown in Fig. 10.

Figure 9 *Object with artificial defect on right side*
Slika 9. *Objekt s umjetnim oštećenjem na desnoj strani*

Figure 10 *Object with artificial defect on left side*
Slika 10. *Objekt s umjetnim oštećenjem na lijevoj strani*

4.1
Digital hologram pictures
Snimke digitalnih holograma

Digital holograms were recorded with ISO 400 and 1/5 shutter speed. Fig. 11 shows a digital hologram of the object with errors caused with the object wave and reference wave intensities. The object had no artificial defects and the recorded digital hologram will be a reference hologram. There is a black pixel area on the right side of the recorded hologram which is the effect of the CMOS sensor position in the digital camera. The sensor is placed in the back side of the camera and front opening is not wide enough to pass through reference wave to illuminate the whole sensor.

From intensities in Fig. 11 it is necessary to subtract the intensities of the object wave intensities and then the reference wave intensities. The result is shown in Fig. 12 with adjusted brightness.

The same procedure was performed on the same object but in all other cases the object had some artificial defect in the form of wrinkled black paper with 3-4 mm^2 area. One of the holograms was made with artificial defect on the right side of the object and the other hologram was made with artificial defect on the left side of the object. There are no visually detectable dissimilarities in the holograms made from the object with defects compared to the reference hologram. Next step in the DDH method is subtracting reference hologram with all other holograms resulting in difference holograms.

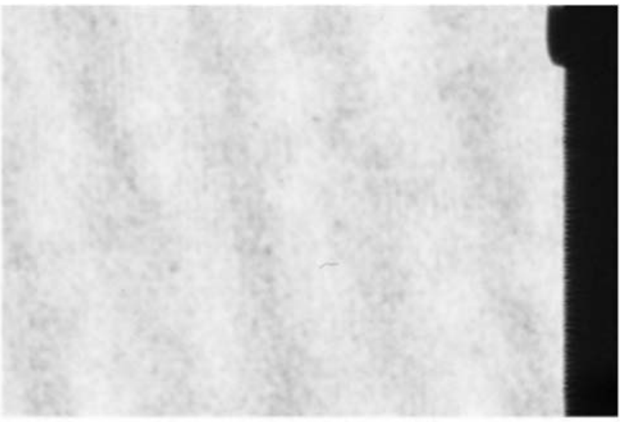

Figure 11 *Digital hologram of object with no defects*
Slika 11. *Snimka digitalnog holograma objekta bez pogrešaka*

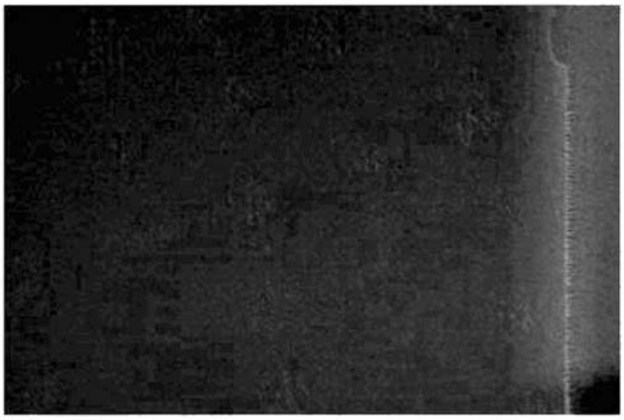

Figure 12 *Digital hologram intensities with subtracted object and reference wave intensities*
Slika 12. *Intenziteti digitalnog holograma s oduzetim intenzitetima objektnog i referentnog vala*

5
Result analysis
Analiza rezultata

This part of the paper will be dealing with analysis of the recorded holograms and difference holograms. Prearrangement of data to be analyzed was performed with C# program that creates a histogram of pixel intensities from recorded pictures for each color component in the BMP picture. The program was written in C# to be used for data preparation from all recorded holograms and difference holograms. Results were fed into Microsoft Excell 2007 for further analysis. Calculated frequencies are graphically presented on the following charts. It is very important to emphasize that only the first 60 frequencies were considered for analysis because higher frequencies have zero value. These frequencies represent pixel intensities values and they can be observed on recorded holograms only if brightness is increased. Analysis was made on every color component separately.

Red hologram component histogram shown in Fig. 13 has high frequencies in low pixel intensities values, but distribution is somewhat similar for all holograms. There is a visible shift of maximum frequency value in the green hologram component histogram shown in Fig. 14. Maximum frequency values for both holograms with errors

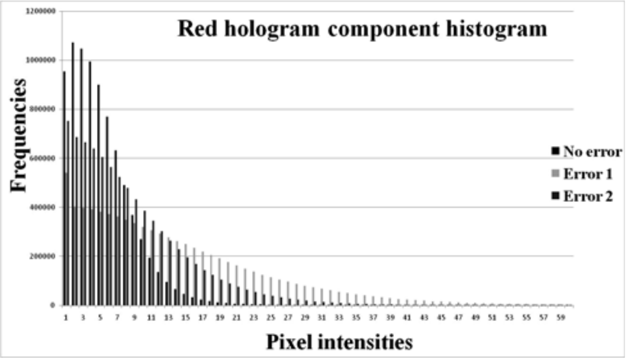

Figure 13 *Red hologram component histogram*
Slika 13. *Histogram crvene komponente holograma*

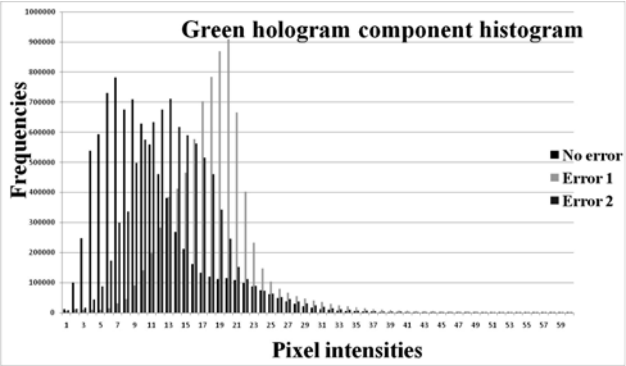

Figure 14 *Green hologram component histogram*
Slika 14. *Histogram zelene komponente holograma*

are shifted towards the higher pixel intensity values. Maximum frequency value for the hologram with error 2 is shifted by value 7 and maximum frequency value for the hologram with error 2 is shifted by value 14 compared to the hologram without errors.

The blue hologram component histogram shown in Fig. 15 is very similar to the red hologram component histogram. That is because the light source used to create the holograms is green laser so the red and the blue hologram components can be considered as noise. Dissimilarities in the recorded holograms are best observed in green hologram component. Therefore, the red and blue hologram component histograms will not be further analyzed.

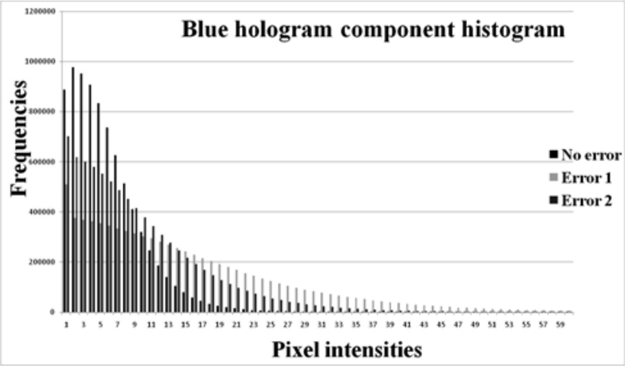

Figure 15 *Blue hologram component histogram*
Slika 15. *Histogram plave komponente holograma*

Similar frequency distributions can be observed in Figures 14 and 16. That means that analysis can be performed both on holograms and difference holograms. One advantage of performing the analysis on holograms is shorter time of calculations because difference holograms have one more step in calculation (subtracting reference hologram and any other hologram). Difference hologram calculation time depends on raw computer calculation power (CPU frequency, number of physical cores in CPU) and bitmap picture resolution (higher picture resolution results in longer calculation time).

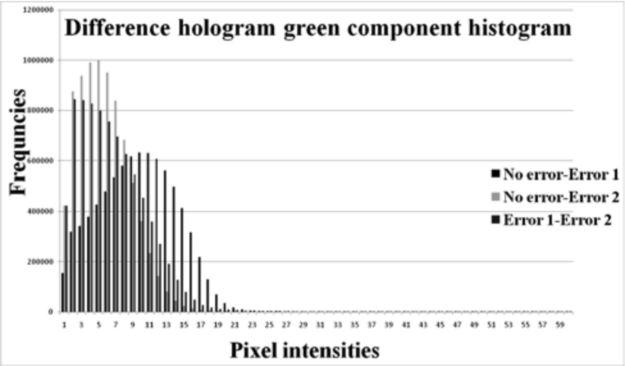

Figure 16 *Difference hologram green component histogram*
Slika 16. *Histogram zelene komponente razlike holograma*

Table 1 *Hologram and difference hologram intensities mean values*
Tablica 1. *Srednje vrijednosti intenziteta holograma i razlika holograma*

	Red	Green	Blue
No error	4,337806	9,419334	4,871567
Error 1	14,909680	20,134740	16,196470
Error 2	7,479199	13,200370	8,529790
Difference 1 No error-Error1	12,162720	11,284870	13,069198
Difference 2 No error-Error2	5,550571	4,791187	6,335724
Difference 3 Error 1-Error 2	11,471400	8,017208	12,363576

Hologram with no error has the lowest mean value of pixel intensities in all three components. Mean values of pixel intensities for the hologram with error 1 and error 2 are 213,76 % and 140,14 % of the mean value for the hologram with no errors, respectively.

There is one advantage in performing analysis on difference holograms. During the process of recording holograms with digital camera Canon EOS 30D CMOS sensor was exposed to dust that accumulates during the recording process. Artifacts caused by dust are unwanted. Fig. 17 shows the recorded hologram consisting of all three color components (RGB) with marked dust artifacts.

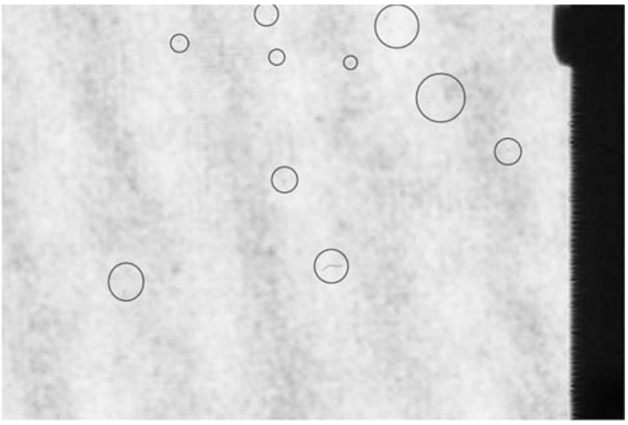

Figure 17 *Dust artifact in recorded hologram*
Slika 17. *Smetnja uzrokovana nakupljanjem prašine*

Dust artifacts in the same positions are still visible on difference hologram with all three color components as shown in Fig. 18.

Figure 18 *Difference hologram – all color components*
Slika 18. *Razlika holograma – sve tri komponente*

Figure 19 *Difference hologram - red component*
Slika 19. *Razlika holograma - crvena komponenta*

Figure 20 *Difference hologram - green component*
Slika 20. *Razlika holograma - zelena komponenta*

Difference hologram color components were separated. Both red (Fig. 19) and blue (Fig. 21) difference hologram color components have dust artifacts visible in the same position as in the whole difference hologram (Fig. 18). Dust artifacts are not visible only in Fig. 20 which shows the difference hologram green color component. This phenomenon can be related to the light source used in the experiment – green laser light source. Further experiments will be dealing with this phenomenon.

Figure 21 *Difference hologram - blue component*
Slika 21. *Razlika holograma - plava komponenta*

6
Conclusion
Zaključak

This paper presents a new method applicable in quality control called differential digital holography. The proposed method can be applied in processes where the product is a 3D object and only one side of the object has to be analyzed to detect production defects on the object – like ceramic tiles manufacturing process. Each product is somehow compared to the reference object in hologram domain. This paper has shown that analysis can be performed on histograms to detect whether the product has some defects. The method is applicable on holograms and on difference holograms (holograms made by subtraction of reference hologram and any other hologram). The DDH method stores data in the form of 2D pictures that contains some information about the third dimension of the recorded object. The object side visible to the sensor will be recorded as a hologram.

The proposed method has some disadvantages. The first one is that the DDH method is highly sensitive to any kind of vibrations. The other disadvantage is the calculation time necessary to calculate difference holograms and prepare histograms. Both disadvantages can be overcome. Vibrations can be eliminated by damper installing and calculation time can be shortened by using computers with several cores and by parallel programming.

Calculating time depends on the recorded picture size. Higher resolution means longer calculating time. Physical dimensions of sensor and sensor resolution are conditions that dictate minimal distance between the object and the sensor.

DDH method can detect small differences between holograms. The analysis is performed on 2D pictures to detect defects that are in the third dimension.

7
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