Image Processing in Differential Digital Holography (DDH)

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Abstract: *Accumulating dust on Charge-Coupled Device/Complementary Metal-oxide-Semiconductor (CCD/CMOS) sensors can cause problems in detecting defects on observed object in some industrial production. This paper describes Differential Digital Holography (DDH) and observed effect of cancelling the negative impact of dust on optical sensor. The laboratory setup for recording digital holograms is described and shown graphically later in paper. Differential digital holography method is presented step by step. Furthermore, negative effect of accumulating dust on CCD/CMOS sensor and cancelling effect due to DDH method is explained. DDH method comprises of both hardware and software parts. Digital hologram recording process takes place on hardware and all image, i.e., digital hologram, while processing is performed by intensive calculations on processor. Experiments were conducted and graphical results are shown.*

Keywords: *CCD/CMOS image sensors, digital holography, dust, holographic optical components, Image processing.*

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1. Introduction

With the appearance of laser back in the middle of 20th century, the new era of hologram practical use began [12]. The term holography represents recording of whole information instead of intensities only, enabling the recording and reconstruction of scattered object light. Hologram is represented as an interference pattern (fringe) of the object wave and the reference wave in the plane where the recording medium, i.e., optical sensor, is placed. Holography consists of writing and reading process, where writing implies collection of amplitude and phase information, and reading implies process where hologram is illuminated with reference light source [24]. Thus we can conclude that hologram contains amplitude and phase information about the object placed on the recording scene. One could say that object information about the third dimension is recorded in two-dimensional picture.

Digital holography [13, 29] is a branch of science and technology which represents improvement in the area of holography. In digital holography, hologram is recorded by using discrete electronic devices Charge-Coupled Device/Complementary Metal-oxide-Semiconductor (CCD, or CMOS optical Sensors), mirrors and beam splitters [19]. There is one significant advantage of digital holography over classic analogue holography. That refers to the ability of writing and recording a large number of holograms digitally, where limitation is amount of memory for storing digital holograms.

There are two different laboratory setups for digital hologram recording process, inline and off-axis, where inline means that referent and object waves are spreadin line thus causing problems such as twin image problem [27, 31], and off-axis where referent and object waves are spread in different directions thus solving problem such as twin image [2, 10, 18, 22, 30].

Efficiency of digital holography depends entirely on recorded hologram resolution which nowadays is not a problem since modern digital CCD cameras with over 8 million pixels are standard. Although, the advantage and potential application of holography over standard photography is obvious, photography is still more represented technique in almost all image processing areas [24].

Still, digital holography found application in numerous areas such as measurement of microscopic objects, 3D object recognition, microsystems, sea exploration, analysis of radiating structures, medical image processing, different industry applications like control of tiles production etc. [9, 10, 15, 16, 20, 23, 25, 26, 28], encryption in image/video technology [11].

Differential Digital Holography (DDH) method uses bared CCD/CMOS sensor for recording digital holograms. Any transparent material attached to a light sensor (CCD/CMOS) or placed on the path of the object wave can result in faulty hologram information detected on optical sensor. To avoid faulty hologram information bare CCD/CMOS sensor is used as well as other optical components like beam-splitter and mirrors. Industrial production lines such as tiles production lines contain a lot of dust that can cause various problems such as interference with the normal operation of the system for taking photos or videos. Accumulated dust on optical components, like optical lenses and optical sensors, corresponds to noise and errors in recorded data. Such errors may complicate the execution of algorithms for detecting defects on final product [5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 21]. Therefore, the main focus of this work is accumulated dust only on optical sensor while recording digital holograms in industrial production. Method for detecting defects on final product including software solution using digital holography and observed effect of cancelling negative impact of accumulated dust [14, 15, 16, 17] will be explained in detail. Also, the explanation of software solution is included.

The main contribution of this paper is proposed method called differential digital holography.

This paper is organized as follows: section 2 gives mathematical description of a hologram. Object wave and reference wave that interfere into off-axis hologram are also mathematically described in this section. Section 3describes proposed method and equipment used to record digital holograms. Modifications of base laboratory setup are presented as well as step-by-step explanation and calculation of difference hologram, including software solution. Section 4 shows results of conducted experiments. Section 5 concludes the paper with end view on some methods for shortening the time of calculations [1].

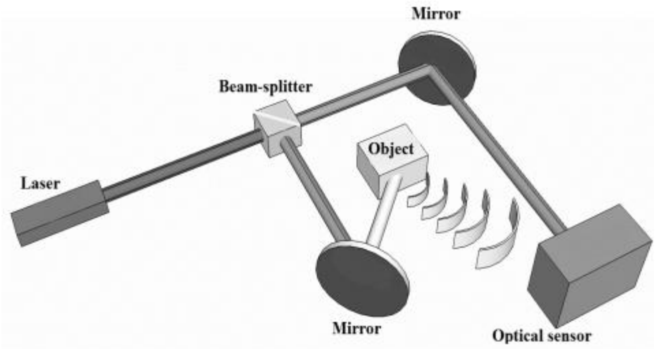


Figure 1. Laboratory setup for digital hologram recording process.

2. Mathematical Description of a Hologram

This section explains mathematical description of off-axis hologram and its consequences. Laboratory setup is shown in Figure 1.

Reference wave can be written as:

$$\hat{R}(x,y) = \hat{A}_R(x,y)e^{i[\hat{\varphi}_R(x,y)]} \quad (1)$$

where $\hat{A}_R(x,y)$ represents reference wave complex amplitude and $\varphi_R(x,y)$ represents reference wave complex phase. Object wave can be written as follows:

$$\hat{O}_{\Delta\varphi}(x,y) = \hat{A}O_O(x,y)e^{i[\hat{\varphi}_O(x,y)+\Delta\hat{\varphi}]} \quad (2)$$

where $\hat{A}_O(x,y)$ is object wave complex amplitude and $\hat{\varphi}_O(x,y)$ is object wave complex phase. Object and reference wave are not aligned in phase and there is some phase difference given by the expression $\Delta\hat{\varphi}$ in Equation (2).

Interference pattern $\hat{H}(x,y)$, complex interference wave, created on the surface of the recording medium can be written as superposition of two complex waves as follows:

$$\hat{H}(x,y) = \hat{O}_{\Delta\varphi}(x,y) + \hat{R}(x,y) \quad (3)$$

Optical sensor is able to detect and record only light intensity without any phase information. Result of the recording process of the interference pattern on the surface of the optical sensor can be written as:

$$\hat{H}^2(x,y) = \quad |\hat{O}_{\Delta\varphi}(x,y) + \hat{R}(x,y)|^2 \quad (4)$$

3. Differential Digital Holography

Differential digital holography has been developed with the aim of monitoring the quality of the final product of a manufacturing process [7]. The method is based on the recording of digital hologram [3, 4] of an object using CCD/CMOS sensor consisted of photo-active area and transmission area connected to computer. Term 'differential' in the method name refers to comparison of an object hologram without manufacturing defects and other holograms of manufacturing objects which may contain some defects in the 3rd dimension.

All holograms and difference holograms are separated in basic colour components-red, green and blue before any analysis. This paper will show that only one colour component is sufficient for analysis and exactly that colour is laser light source.

3.1. Equipment used in Experiments

Laboratory setup used to record holograms consists of following components:

- LASER - source of coherent light
- Beam splitter - dimensions: 30 x 50 mm
- Mirrors
- Digital camera with bare CMOS sensor

Light source used in the experiment was green laser with wavelength λ=532nm and output power less than 50mW. This light source has to be coherent because of possibility of interference of an object wave and reference wave on the optical sensor surface. Laboratory setup used in experiments consists of digital camera with built-in CMOS optical sensor instead of standalone CMOS sensor thus avoiding the designing and implementing additional electronic circuits for communication with the computer. Digital camera used in experiments was Canon EOS 30D with 8Mpix CMOS optical sensor, USB interface for connection with computer and Compact Flash memory card. It is important to note that the optical lens has to be removed from the body of digital camera in order to record digital hologram. Optical lens mounted on the body of digital camera prevents hologram recording because lens system affects optical path of the incident wave.

3.2. Laboratory Setup Modifications

Before digital hologram recording process takes place, laboratory setup shown in Figure 1 has to be modified. Hologram equation can be written as:

$$I(x,y) = O^2_{\Delta\varphi}(x,y) + R^2(x,y) + O^*_{\Delta\varphi}(x,y)R(x,y) + O\Delta\varphi(x,y)R^*(x,y) \quad (5)$$

Where expressions $O^2_{\Delta\varphi}(x,y)$ and $R^2(x,y)$ represent offset in the intensities of the object wave and reference wave. The rest of the (4) expression represents twin image hologram. Sequence of figures will show how to make modifications in laboratory setup. First step in the process is hologram recording using unmodified laboratory setup shown in Figure 2. In order to remove first intensity offset it is necessary to prevent reference wave to reach optical sensor. It is performed by placing opaque obstacle in the reference wave path as shown in Figure 3 thus allowing only object wave intensities to be recorded. The last step is to record reference wave by placing opaque obstacle in the object wave path resulting in total blocking of object wave intensities as shown in Figure 4. After all three types of setups shown in Figures 2, 3 and 4 are tested, further processing is needed and described in the following chapters.

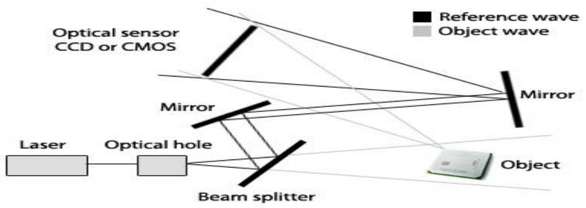


Figure 2. Laboratory setup for recording holograms with offset errors.

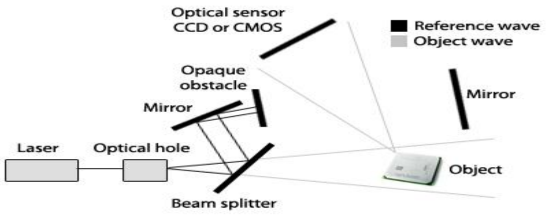


Figure 3. Laboratory setup for recording object wave.

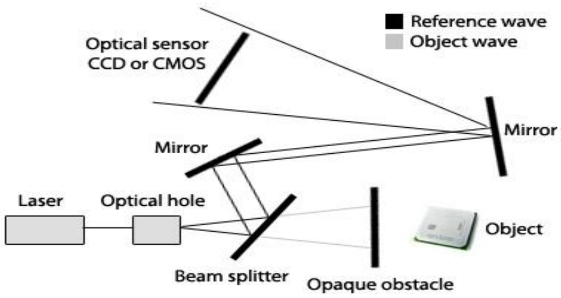


Figure 4. Laboratory setup for recording reference wave.

3.3. DDH Method Step-by-Step

Differential digital holography method is performed in several steps. Before any hologram recording takes place, it is crucial to select reference object that contains no defects. This step is crucial because hologram of the reference object is used to compare with holograms of all other objects.

It is very important to note that all holograms have to be same in size (pixel width and height) so calculations can be performed on pixel level. This requirement should not be a problem because same optical sensor is used for recording all holograms. It is necessary to perform following steps:

1. Reference object selection.
2. Reference object hologram recording.

   a. Recording intensities of the interference pattern of the object wave and reference wave (separation in colour components- R, G, B).
   b. Recording intensities of the object wave (separation in colour components – R, G, B).
   c. Recording intensities of the reference wave (separation in colour components – R, G, B).
   d. Twin hologram intensities calculation – hologram without intensities offsets errors (a - b - c, in each component separately).

3. All other objects hologram recording (steps from a through d).
4. Calculating difference hologram (2d - 3d).
5. Result analysis.

Platform used to perform calculations consists of Intel Core i5 2430M processor at 2.4 GHz and 4 GB DRAM DDR3 memory at 665.1 MHz.

Calculation times for both algorithms executed on computer with given specifications are 36.2536607 seconds for subtracting images and 35.3179475 seconds for separating colour components of an image. Execution time values are approximately the same because both algorithms perform calculations on images of same size. Separation process needs 0.9357132 seconds less than subtraction because it processes only one image while subtraction processes two images.

3.4. Software Implementation

Software part of DDH method is performed as series of calculations that takes place on Central Processing Unit (CPU). Steps necessary to acquire differential digital hologram are listed in Section III. C. from step 2.d through 4. This section will explain algorithms used to perform those steps. All algorithms are written in C# programming language.

First step in software implementation is to remove object and reference wave offsets from hologram. There are three pictures necessary to perform this step:

- Digital hologram intensities of an object containing both offsets caused by selected off-axis laboratory setup. Real and imaginary holograms are not on the same area in the recorded digital hologram thus allowing analysis without removing imaginary hologram.

$$I_{DHO}(x, y) \tag{6}$$

where DHO represents digital hologram with both offsets at (x, y) pixel coordinates.

- Reference wave intensities representing light source wave intensities (offset).

$$I_R(x, y) \tag{7}$$

where R represents reference wave.

- Object wave intensities (offset)

$$I_O(x, y) \tag{8}$$

where O represents object wave.

All three mentioned images have to be the same in size in order to perform necessary calculations. Digital hologram intensities without both offsets is acquired by subtracting both offsets from recorded digital hologram. Following expression represents mentioned operation:

$$I_{DH}(x, y) = I_{DHO}(x, y) - I_R(x, y) - I_O(x, y) \tag{9}$$

where $I_{DH}(x, y)$ represents digital hologram intensity without both offsets (I_{DH}) at position (x, y). This step is performed for each colour component separately and that means expression (9) will be used for red, green and blue colour component.

Calculation of the difference hologram intensities is performed by subtracting intensities of the pixels on the holograms at the same position according to:

$$I_{DHi}(x, y) = I_{RH}(x, y) - I_{Hi}(x, y) \tag{10}$$

Where $I_{DHi}(x, y)$ represents difference hologram intensities at position (x, y), $I_{RH}(x, y)$ represents reference hologram intensities at the same position and $I_{Hi}(x, y)$ represents any other hologram. Expression (10) is used for each colour component, that is, same expression is used three times – each time for other colour component (R, G, B) resulting in three colour components of difference hologram.

Algorithm 1 presents algorithm for difference hologram calculation and algorithm 2 presents algorithm for separating colour components.

Algorithm 1:Pseudo code for difference hologram calculation

```
for each i from 0 to image_width
  for each j from 0 to image_height
    r1 = get_red_pixel_value_hol1(i,j)
    r2 = get_red_pixel_value_hol2(i,j)
    g1 = get_green_pixel_value_hol1(i,j)
    g2 = get_green_pixel_value_hol2(i,j)
    b1 = get_blue_pixel_value_hol1(i,j)
    b2 = get_blue_pixel_value_hol2(i,j)
    r = r1 – r2
    g = g1 – g2
    b = b1 – b2
    diff_hol.set_pixel(i,j).values(r,g,b)
  end for each j
end for each i
```

Algorithm 2:Pseudo code for separating colour components

```
for each i from 0 to image_width
  for each j from 0 to image_height
    r = hologram.get_red_pixel_value(i,j)
    g = hologram.get_green_pixel_value(i,j)
    b = hologram.get_blue_pixel_value(i,j)
    red_hol.set_pixel(i,j).value(r,0,0)
    green_hol.set_pixel(i,j).value(0,g,0)
    blue_hol.set_pixel(i,j).value(0,0,b)
  end for each j
end for each i
```

4. Results

This section will present obtained results before and after the DDH method was applied to digital holograms. Figure 5 shows hologram of referent object with offsets in intensities values caused by object and reference wave. Hologram dimensions are 3504 pixels in width and 2336 pixels in height. Main area of interest is marked with 200 x 150 pixels rectangle. Top left corner of rectangle has coordinates (1700, 1400) and bottom right corner coordinates are (1900, 1550). Mentioned area is not the only one that contains dust artefacts but it is the easiest to observe. There is black area in the right side of hologram caused by the geometry of laboratory setup and digital camera architecture. Optical sensor in digital camera is placed closer to the back side blocking the path of small part of reference and object wave. It has no influence on method calculations.

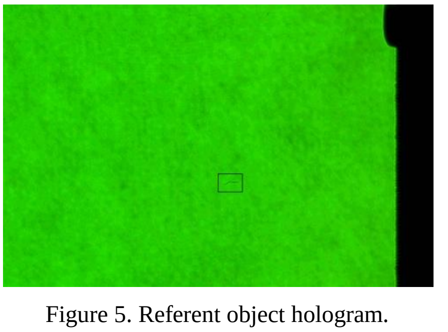


Figure 5. Referent object hologram.

Hologram shown in Figure 5 can be separated in Red, Green, Blue (RGB) colour components. Dust artefact can be observed by visually inspecting recorded hologram. Mentioned artefact can negatively affect image analysis results. Thus, DDH method will be applied which is shown graphically later in this section. All three colour components are shown in Figures 6 through 8.

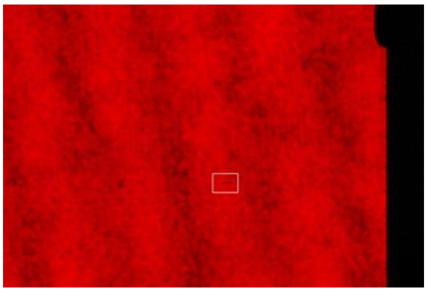


Figure 6. Red colour component.

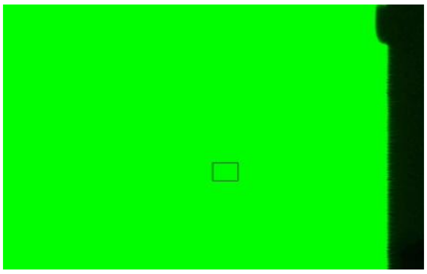


Figure 7. Green colour component.

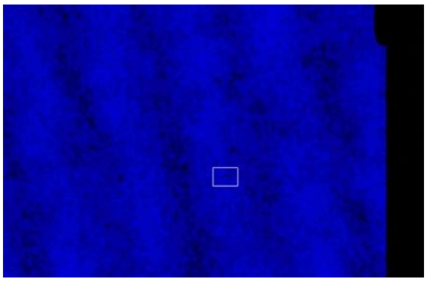


Figure 8. Blue colour component.

Both red and blue colour components contain dust artefact in the same position. Dust artefact cannot be observed in green colour component because green component intensities are significantly greater in value than the rest two components. Figure 9 shows referent object hologram intensities after subtraction of reference and object wave. After this subtraction hologram is cleared from intensities offsets that introduce errors in hologram intensities values.

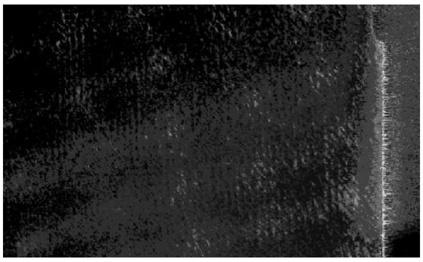


Figure 9. Hologram pixel intensities without offsets.

Dust artefact is still present but it is barely noticeable in red and blue colour component, but it seems that dust artefact is no longer present in green colour component. Selection box pixel intensities from Figure 9 RGB components will be shown in numerical values to confirm presence of dust artefact. Selection box pixel intensities are show in Figures 10, 11 and 12 for each colour component but observed pixels are taken from slightly smaller area than selection box. Coordinates of pixels with shown numerical values are: top left corner (1785, 1455) and bottom right corner (1917, 1500).

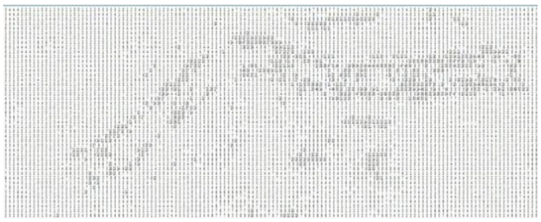


Figure 10. Red colour component selection box pixel intensities values of referent hologram.

Figure 11. Green colour component selection box pixel intensities values of referent hologram.

Figure 12. Blue colour component selection box pixel intensities values of referent hologram.

Shape of the dust artefact can be observed in numerical values in red and blue colour components but not in green colour component. There is still one step in differential digital holography method to perform. Intensity values of hologram taken from object with artificially made defect have to be subtracted from intensity values of hologram taken from reference object resulting in difference hologram intensity values shown in Figure 13.

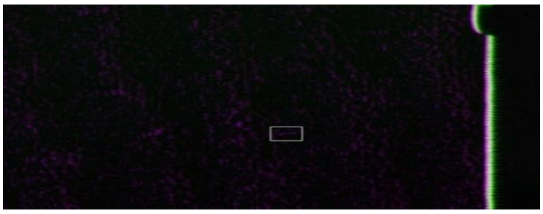


Figure 13. Difference hologram with all three colour components.

Again, dust artefact can be noticed in both red and blue colour components but not in green colour component. Verification will be presented in the form of numerical values of pixel intensities of area where the dust artefact is observed. Coordinates of pixels with shown numerical values are: top left corner (1785, 1455) and bottom right corner (1917, 1500).

Figure 14. Red colour component selection box intensities values of difference hologram.

Figure 15. Green colour component selection box pixel intensities values of difference hologram.

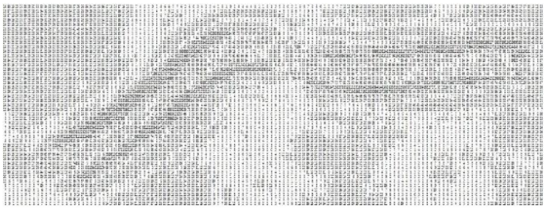


Figure 16. Blue colour component selection box pixel intensities values of difference hologram.

The same procedure has been performed on other segments of difference hologram to test the hypothesis of cancelling negative effect of accumulated dust. Figure 17 shows rectangular segments of hologram (100×100 pixels) that have been examined, without the already examined segment.

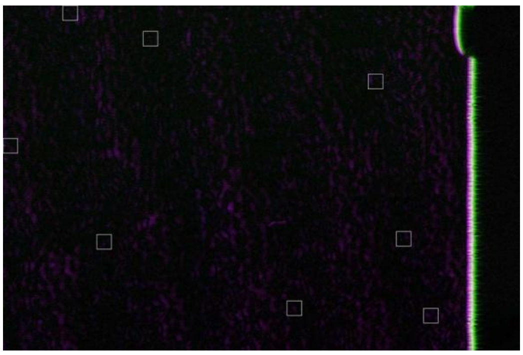
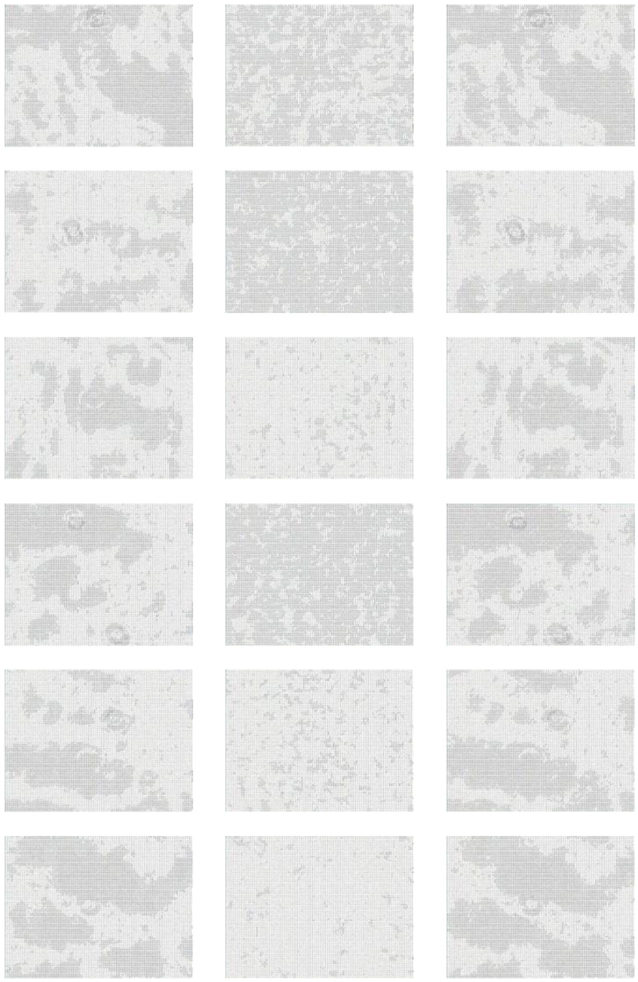


Figure 17. Difference hologram with all three colour components and 8 segments for testing.



a) red. b) green. c) blue.

Figure 18. Colour component selection box pixel intensities values of difference hologram – 24 images.

Coordinates of upper left segment corners are given inTable 1.

Table 1. Upper left coordinates of 8 marked segments on Figure 17.

Upper left segment coordinates	
x	y
0	900
405	0
635	1550
950	175
1925	2000
2475	465
2665	1530
2850	2050

Cancelling effect of negative influence of accumulated dust can be observed only in green colour component of difference hologram as shown in series of pictures that represent pixel intensities of all three difference hologram colour components in Figure 18. Both red and blue colour components have visible dust artefact in difference hologram.

5. Conclusions

Dust accumulation on the surface of optical sensor may occur during the process of digital hologram recording. Such accumulated dust has negative influence on image (hologram) quality and it is manifested by the appearance of different artefacts shown in Figure 5. Proposed method for cancelling the negative impact of accumulated dust gives positive results. This paper shows that the cancellation effect of the negative impact of dust occurs only in the colour component close to laser source colour. Since green laser light source was used cancellation effect can be observed only in green colour component of recorded hologram. Although, measuring of algorithms performance is out of scope of this paper, calculation time needed to calculate difference holograms and reproduce results is one of the main disadvantages of this approach. Obtained results are closely related to picture resolution where higher picture resolution means greater calculation time. There are certain ways to improve execution time. This can be achieved mainly by parallelization whether on GPUs or CPUs which will surely be the topic of our future work.

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