Estimating the quality of stereoscopic endoscopic systems

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Abstract. Stereoscopic video endoscopic systems are widely used for the control of hard-to-reach objects at the stages of production, assembly and testing of various devices. Using a stereoscopic endoscope as a measuring tool requires its geometrical calibration. The effectiveness of such systems is largely determined by the quality of an image, based on modulation transfer function (MTF) of the optical system. In this paper, we describe and test an algorithm for automatic calculating the MTF for images of a plane test object with chessboard pattern. Experimental data was obtained using two self-developed prism-based endoscopic stereoscopic systems. Coincidence of computer simulation results and results of applying the proposed algorithm shows its effectiveness for estimating the image quality provided by stereoscopic endoscopic systems.

1. Introduction

Currently, stereoscopic video endoscopic systems are a key tool for non-destructive testing of hard-to-reach elements in complex technical systems, such as aircraft engines, steam generators, etc. Due to small diameter of the endoscopic probe, stereo images in such devices are usually formed by the prism, which creates two images of the inspected surface on the camera sensor [1].

To use a stereoscopic endoscope as a measuring tool, it is necessary to calibrate it as a stereo system [2]. Known methods require a plane test object with chessboard pattern, located in several positions inside the working volume of the system [3, 4]. Additionally, it is necessary to estimate the quality of the image obtained by the system, because it affects the accuracy of 3D surface reconstruction. The image quality depends on the noise generated by the sensor and the electronic circuits as well as on the distortions introduced by an optical system. According to the standard [5], the slanted-edge method of MTF measurement is used to estimate the performance of the optical system.

We propose to use the same plane test object with chessboard pattern to perform calibration and assess image quality for the stereo endoscope. Such an object contains both areas of inclined boundaries required for measuring the MTF and areas of constant intensity suitable for estimating noise parameters. It will significantly reduce the required time and cost of auxiliary equipment.
because estimations of MTF, distortion and noise, as well as calibration can be performed simultaneously.

In this paper, we experimentally demonstrate MTF measurements for two self-developed endoscopic stereoscopic probes using the images of chessboard patterns, like for calibration procedure. We compare the results obtained using these systems at three working distances and theoretical dependencies calculated for these optical systems in optical design software Zemax.

2. Instruments and methods

We carried out MTFs estimation for two self-developed prism-based stereo endoscopic systems, which technical characteristics are presented in table 1. We further denote these systems as OS1 and OS2.

| Feature                  | OS1                      | OS2                      |
|--------------------------|--------------------------|--------------------------|
| Matrix diagonal          | 1/9”                     | 1/6”                     |
| Matrix resolution        | 1280 × 720               | 1920 × 1080              |
| Pixel size               | 1.4 × 1.4 µm²            | 1.4 × 1.4 µm²            |
| Image format             | 24 bit, RGB              | 8 bit, Grayscale         |
| Field of view per channel| 35° × 40°                | 40° × 45°                |
| Aperture                 | F/8                      | F/11                     |
| Effective focal length   | 1.8 mm                   | 2.36 mm                  |

The optical layouts of these systems are similar (figure 1). More information about the design of prism-based stereoscopic endoscopes may be found in [6] and [7].

![Stereoscopic optical system](image)

**Figure 1.** Scheme of MTF measurements for prism-based stereoscopic endoscopes.

The prism introduces significant aberrations, which can not be completely corrected by the lens system. These aberrations vary significantly across the field of view, so 9 field points in each channel were used for MTF assessment. The exact coordinates of these points are presented in table 2. MTF calculation for each image point was carried out in Zemax for three object distances (7, 15 and 40 mm from the protective glass, as shown in figure 1). The distances correspond to the boundaries and the middle of the working distance range of the system. The obtained data was exported from Zemax and then was processed in MATLAB.
Table 2. Points coordinates for MTF estimating.

| System type | OS1 |  | OS2 |  |
|-------------|-----|---|-----|---|
| Point number | Image coordinate (px) | Zemax image coordinate (mm) | Image coordinate (px) | Zemax image coordinate (mm) |
| 1 | 80 | 80 | -0.784 | -0.392 | 80 | 80 | -1.232 | -0.644 |
| 2 | 80 | 360 | -0.784 | 0 | 80 | 540 | -1.232 | 0 |
| 3 | 80 | 640 | -0.784 | 0.392 | 80 | 1000 | -1.232 | 0.644 |
| 4 | 320 | 80 | -0.448 | -0.392 | 480 | 80 | -0.672 | -0.644 |
| 5 | 320 | 360 | -0.448 | 0 | 480 | 540 | -0.672 | 0 |
| 6 | 320 | 640 | -0.448 | 0.392 | 480 | 1000 | -0.672 | 0.644 |
| 7 | 560 | 80 | -0.112 | -0.392 | 880 | 80 | -0.112 | -0.644 |
| 8 | 560 | 360 | -0.112 | 0 | 880 | 540 | -0.112 | 0 |
| 9 | 560 | 640 | -0.112 | 0.392 | 880 | 1000 | -0.112 | 0.644 |
| 10 | 720 | 80 | 0.112 | -0.392 | 1040 | 80 | 0.112 | -0.644 |
| 11 | 720 | 360 | 0.112 | 0 | 1040 | 540 | 0.112 | 0 |
| 12 | 720 | 640 | 0.112 | 0.392 | 1040 | 1000 | 0.112 | 0.644 |
| 13 | 960 | 80 | 0.448 | -0.392 | 1440 | 80 | 0.672 | -0.644 |
| 14 | 960 | 360 | 0.448 | 0 | 1440 | 540 | 0.672 | 0 |
| 15 | 960 | 640 | 0.448 | 0.392 | 1440 | 1000 | 0.672 | 0.644 |
| 16 | 1200 | 80 | 0.784 | -0.392 | 1840 | 80 | 1.232 | -0.644 |
| 17 | 1200 | 360 | 0.784 | 0 | 1840 | 540 | 1.232 | 0 |
| 18 | 1200 | 640 | 0.784 | 0.392 | 1840 | 1000 | 1.232 | 0.644 |

The setup shown in figure 2 was used to obtain experimental data. The glass plate with chrome-etched chessboard pattern (2 mm chessboard cell size) was combined with white diffusing glass and illuminated from behind by a white-light source.
Figure 2. Setup for measuring MTF of stereoscopic optical systems.

Images of the test object were acquired at three distances of 7, 15 and 40 mm from the protective glass of the optical system for both endoscopes. MTF estimation was carried out in areas containing slanted high-contrast edges. The regions of estimation were chosen closely to the points used for MTF calculation in Zemax. Image processing and calculation of the MTF were performed according to the standard technique [5, 8]. For each region, a subpixel profile of the brightness difference on the boundary was constructed, then the Fourier transform of the derivative of the subpixel profile was calculated and normalized on the maximum value. An example of an image with highlighted points for MTF calculation in Zemax (green points) and areas for MTF estimation using image processing (red rectangles) is shown in figure 3 (here, we show the areas for measuring MTF in the vertical direction).

Figure 3. The image of the test object with highlighted points for MTF calculation in Zemax (green points) and areas for MTF estimation using image processing (red rectangles).
3. Results

We compared 2 calculated (in horizontal and vertical directions) and 2 experimental MTF curves as well as the values of spatial frequencies, at which the contrast values of 0.1 and 0.5 were achieved. The results are given in figures 5-7 and tables 4-6 for OS1 at three working distances. The results for OS2 are presented in figures 8-10 and tables 7-9.

The values in the tables are divided into the following subgroups:
- Left and Right channel - the channel of the stereo image in which the MTF is estimated.
- Level 0.5 and Level 0.1 - MTF levels necessary to define the key values of spatial frequencies.
- “Hor.” and “Ver.” - are horizontal and vertical directions respectively, used for MTF estimation.

Figure 4 presents the legends used for figures 5-10.

| Description                                      | Denotation |
|--------------------------------------------------|------------|
| Estimated modulus of MTF in horizontal direction | -          |
| Zemax modulus of MTF in horizontal direction     | - -        |
| Estimated modulus of MTF in vertical direction   | - -        |
| Zemax modulus of MTF in vertical direction       | - -        |
| 0.5 and 0.1 levels of MTF modulus                | --         |

**Figure 4.** Legends for figures 5-10.

**Figure 5.** Estimated MTF at 18 points for OS1. Distance to the test object is 7 mm.
Table 3. The spatial frequencies at 0.5 and 0.1 levels of MTF for OS1 (in mm\(^{-1}\)). Distance to the test object is 7 mm.

| Point’s number | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  |
|----------------|----|----|----|----|----|----|----|----|----|
| **Left channel** |    |    |    |    |    |    |    |    |    |
| Level 0.5 | Zemax | 41  | 39.2 | 38.2 | 38.2 | 39.2 | 41  | 37.2 | 33.3 | 32.5 |
|           | Estimated | 33.3 | 31  | 33.1 | 38.1 | 29.7 | 34  | 30.3 | 31.4 | 29  |
| Level 0.1 | Zemax | 67.8 | 49.4 | 39.3 | 39.3 | 49.4 | 67.8 | 72.4 | 47.7 | 39  |
|           | Estimated | 32.2 | 34.6 | 32.9 | 31.5 | 34.9 | 45.6 | 32  | 34.5 | 31.7 |
| **Right channel** |    |    |    |    |    |    |    |    |    |
| Level 0.5 | Zemax | 104.5 | 102 | 96.4 | 96.4 | 102 | 104.5 | 95.5 | 76.1 | 72.9 |
|           | Estimated | 80.9 | 73  | 70.4 | 88.1 | 71.9 | 76.2 | 97.5 | 73.8 | 78.8 |
| Level 0.1 | Zemax | 158.5 | 109.3 | 70.8 | 70.8 | 109.3 | 158.5 | 164.4 | 108.1 | 71.2 |
|           | Estimated | 75.5 | 79.5 | 64.5 | 67.6 | 80.8 | 99.1 | 72.4 | 75.6 | 69.2 |

| Point’s number | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
|----------------|----|----|----|----|----|----|----|----|----|
| **Left channel** |    |    |    |    |    |    |    |    |    |
| Level 0.5 | Zemax | 32.5 | 33.3 | 37.2 | 41  | 39.2 | 38.2 | 38.2 | 39.2 | 41  |
|           | Estimated | 30.1 | 36.4 | 35.6 | 30.1 | 26.4 | 27.3 | 28.1 | 29.1 | 33.9 |
| Level 0.1 | Zemax | 39  | 47.7 | 72.4 | 67.8 | 49.4 | 39.3 | 39.3 | 49.4 | 67.8 |
|           | Estimated | 33.2 | 39.1 | 48.4 | 33.3 | 32.9 | 34.7 | 32.6 | 39.5 | 50.5 |
| **Right channel** |    |    |    |    |    |    |    |    |    |
| Level 0.5 | Zemax | 72.9 | 76.1 | 95.5 | 104.5 | 102 | 96.4 | 96.4 | 102 | 104.5 |
|           | Estimated | 74.2 | 89.3 | 77  | 70.2 | 71  | 67.3 | 64.8 | 76.8 | 82.3 |
| Level 0.1 | Zemax | 71.2 | 108.1 | 164.4 | 158.5 | 109.3 | 70.8 | 70.8 | 109.3 | 158.5 |
|           | Estimated | 67.5 | 88.3 | 116.4 | 71.2 | 66.9 | 64.6 | 65.7 | 89.5 | 111.7 |

Figure 6. Estimated MTF at 18 points for OS1. Distance to the test object is 15 mm.
Table 4. The spatial frequencies at 0.5 and 0.1 levels of MTF for OS1 (in \text{mm}^{-1}). Distance to the test object is 15 mm.

| Point’s number |  |  |  |  |  |  |  |  |  |
|----------------|---|---|---|---|---|---|---|---|---|
|                | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| Left channel   |   |   |   |   |   |   |   |   |   |
| Level 0.5      |   |   |   |   |   |   |   |   |   |
| Zemax Hor.     | 68.7 | 69.8 | 69.5 | 69.5 | 69.8 | 68.7 | 81.7 | 80.8 | 80.6 |
| Estimated      | 41  | 42.9 | 42.8 | 43.1 | 38.2 | 37.4 | 56.8 | 56.6 | 55.4 |
| Zemax Ver.     | 79.2 | 58.1 | 38.6 | 38.6 | 58.1 | 79.2 | 80.3 | 58.8 | 39.1 |
| Estimated      | 49.8 | 43.8 | 35.2 | 38.8 | 44.2 | 54.5 | 50.6 | 45.4 | 34.5 |
| Level 0.1      |   |   |   |   |   |   |   |   |   |
| Zemax Hor.     | 148.4 | 149.6 | 149.1 | 149.1 | 149.6 | 148.4 | 170.8 | 170.4 | 170.4 |
| Estimated      | 90.7 | 109.2 | 99.4 | 99.9 | 83.3 | 75 | 137.7 | 125 | 133.1 |
| Zemax Ver.     | 169 | 115.2 | 117.8 | 117.8 | 115.2 | 169 | 170.8 | 116.6 | 119.9 |
| Estimated      | 107.6 | 91.9 | 62.5 | 76.4 | 97.5 | 132.6 | 117 | 98.1 | 63.7 |
| Right channel  |   |   |   |   |   |   |   |   |   |
| Level 0.5      |   |   |   |   |   |   |   |   |   |
| Zemax Hor.     | 80.6 | 80.8 | 81.7 | 68.7 | 69.8 | 69.5 | 69.5 | 69.8 | 68.7 |
| Estimated      | 48.4 | 50.9 | 46.9 | 51.4 | 46 | 52 | 44.1 | 45.7 | 51.4 |
| Zemax Ver.     | 39.1 | 58.8 | 80.3 | 79.2 | 58.1 | 38.6 | 38.6 | 58.1 | 79.2 |
| Estimated      | 36.3 | 49.3 | 59.9 | 53.2 | 42.9 | 34.5 | 39.6 | 49.3 | 62 |
| Level 0.1      |   |   |   |   |   |   |   |   |   |
| Zemax Hor.     | 170.4 | 170.4 | 170.8 | 148.4 | 149.6 | 149.1 | 149.1 | 149.6 | 148.4 |
| Estimated      | 118.4 | 123.4 | 108.5 | 111.8 | 106.9 | 126.5 | 107.9 | 116.6 | 113.8 |
| Zemax Ver.     | 119.9 | 116.6 | 170.8 | 169 | 115.2 | 117.8 | 117.8 | 115.2 | 169 |
| Estimated      | 73.8 | 109.4 | 118.5 | 166.3 | 82.3 | 66.4 | 79.2 | 109.7 | 157.4 |

Figure 7. Estimated MTF at 18 points for OS1. Distance to the test object is 40 mm.
Table 5. The spatial frequencies at 0.5 and 0.1 levels of MTF for OS1 (in mm⁻¹). Distance to the test object is 40 mm.

| Point’s number | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   |
|----------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| **Left channel** |     |     |     |     |     |     |     |     |     |
| Level 0.5       |     |     |     |     |     |     |     |     |     |
| Hor. Zemax      | 59.7| 55.4| 54.9| 54.9| 55.4| 59.7| 70.6| 67.9| 68  |
| Estimated       | 43.2| 39.7| 38.8| 39.5| 38.8| 39.4| 59.7| 56.7| 53.5|
| Ver. Zemax      | 62  | 46  | 33.6| 33.6| 46  | 62  | 58.9| 46.2| 33.9|
| Estimated       | 58.6| 41.3| 30.7| 32.8| 48.4| 55.6| 63  | 43.7| 33.3|
| Level 0.1       |     |     |     |     |     |     |     |     |     |
| Hor. Zemax      | 139.9| 133.3| 133.4| 133.4| 133.3| 139.9| 171.2| 170.4| 170.4|
| Estimated       | 85.6| 103.7| 79.3| 86.9| 91.4| 83.7| 146.1| 139.5| 121|
| Ver. Zemax      | 165.2| 99.6| 61.6| 61.6| 99.6| 165.2| 164.3| 100.4| 61.9|
| Estimated       | 127.9| 84.7| 64.4| 66.2| 117.4| 122.1| 149.4| 83.6| 63.1|
| **Right channel** |     |     |     |     |     |     |     |     |     |
| Level 0.5       |     |     |     |     |     |     |     |     |     |
| Hor. Zemax      | 68  | 67.9| 70.6| 59.7| 55.4| 54.9| 54.9| 55.4| 59.7|
| Estimated       | 55  | 55.8| 57.2| 50.3| 52  | 56.3| 53.7| 56  | 65.3|
| Ver. Zemax      | 33.9| 46.2| 58.9| 62  | 46  | 33.6| 33.6| 46  | 62  |
| Estimated       | 35.8| 49.8| 62.1| 60.9| 44.7| 32.6| 38.8| 54.4| 59  |
| Level 0.1       |     |     |     |     |     |     |     |     |     |
| Hor. Zemax      | 170.4| 170.4| 171.2| 139.9| 133.3| 133.4| 133.4| 133.4| 139.9|
| Estimated       | 134.7| 122| 133.7| 111.6| 136.8| 136.8| 140.1| 133.9| 135.5|
| Ver. Zemax      | 61.9| 100.4| 164.3| 165.2| 99.6| 61.6| 61.6| 99.6| 165.2|
| Estimated       | 70.8| 118.2| 165| 131.8| 85.9| 64.6| 69.4| 127.5| 143.8|

Figure 8. Estimated MTF at 18 points for OS2. Distance to the test object is 7 mm.
Table 6. The spatial frequencies at 0.5 and 0.1 levels of MTF for OS2 (in mm\(^{-1}\)). Distance to the test object is 7 mm.

| Point’s number | 1     | 2     | 3     | 4     | 5     | 6     | 7     | 8     | 9     |
|----------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| **Left channel** |       |       |       |       |       |       |       |       |       |
| **Level 0.5**   |       |       |       |       |       |       |       |       |       |
| Zemax           | 29.1  | 33.7  | 33.6  | 33.6  | 33.7  | 29.1  | 28.9  | 28.2  | 29.8  |
| Estimated       | 16.7  | 17.7  | 20.9  | 17.2  | 17.1  | 13.5  | 17.3  | 16.2  | 15.8  |
| **Level 0.1**   |       |       |       |       |       |       |       |       |       |
| Zemax           | 48.1  | 35.8  | 20.6  | 20.6  | 35.8  | 48.1  | 57.7  | 35.9  | 21.5  |
| Estimated       | 24.6  | 21.3  | 20    | 22    | 21.2  | 15.3  | 21.2  | 22.6  | 23.7  |
| **Right channel** |       |       |       |       |       |       |       |       |       |
| **Level 0.5**   |       |       |       |       |       |       |       |       |       |
| Zemax           | 66.5  | 75.3  | 72.4  | 72.4  | 75.3  | 66.5  | 83.1  | 77.9  | 87.6  |
| Estimated       | 49.7  | 36.7  | 46.1  | 35.3  | 47.6  | 29.2  | 55.4  | 43.3  | 33.2  |
| **Level 0.1**   |       |       |       |       |       |       |       |       |       |
| Zemax           | 111.6 | 65.8  | 109   | 109   | 65.8  | 111.6 | 120.8 | 66.9  | 119.7 |
| Estimated       | 66.4  | 61.3  | 60.4  | 56.5  | 48.9  | 38.7  | 46.2  | 51    | 46.1  |

**Figure 9.** Estimated MTF at 18 points for OS2. Distance to the test object is 15 mm.
Table 7. The spatial frequencies at 0.5 and 0.1 levels of MTF for OS2 (in mm\(^{-1}\)). Distance to the test object is 15 mm.

| Point’s number | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  |
|----------------|----|----|----|----|----|----|----|----|----|
| **Left channel** |    |    |    |    |    |    |    |    |    |
| **Level 0.5**   |    |    |    |    |    |    |    |    |    |
| Hor. Zemax      | 39 | 39.2| 37.9| 37.9| 39.2| 39 | 58.9| 60.8| 61.2|
| Hor. Estimated  | 24.4| 21.4| 27.3| 27.3| 21.1| 22.8| 25.4| 24.5| 24 |
| Ver. Zemax      | 57.2| 32.4| 18.9| 18.9| 32.4| 57.2| 54.8| 32.8| 19.3|
| Ver. Estimated  | 27.8| 26.7| 25.4| 26.6| 28 | 19.2| 29 | 35 | 22.9|
| **Level 0.1**   |    |    |    |    |    |    |    |    |    |
| Hor. Zemax      | 76.1| 75.9| 74.9| 74.9| 75.9| 76.1| 123.1| 124.3| 124.7|
| Hor. Estimated  | 51.1| 51.7| 68.7| 65.7| 49.3| 56.5| 74 | 63.7| 57 |
| Ver. Zemax      | 120.9| 60.9| 66.7| 66.7| 60.9| 120.9| 122.2| 61.9| 70.1|
| Ver. Estimated  | 53.4| 76.7| 47.9| 50.8| 62.1| 54.9| 58.4| 80.9| 72 |
| **Right channel** |    |    |    |    |    |    |    |    |    |
| **Level 0.5**   |    |    |    |    |    |    |    |    |    |
| Hor. Zemax      | 61.2| 60.8| 58.9| 39 | 39.2| 37.9| 37.9| 39.2| 39 |
| Hor. Estimated  | 24.3| 22.5| 22.1| 23.8| 26.3| 24.5| 25.5| 23.8| 21.8|
| Ver. Zemax      | 19.3| 32.8| 54.8| 57.2| 32.4| 18.9| 18.9| 32.4| 57.2|
| Ver. Estimated  | 26.7| 31.5| 23.5| 27.7| 30.9| 23 | 23.2| 26.6| 21.9|
| **Level 0.1**   |    |    |    |    |    |    |    |    |    |
| Hor. Zemax      | 124.7| 124.3| 123.1| 76.1| 75.9| 74.9| 74.9| 75.9| 76.1|
| Hor. Estimated  | 59 | 59.1| 59.6| 45.3| 79.3| 70.2| 64.7| 71 | 74 |
| Ver. Zemax      | 70.1| 61.9| 122.2| 120.9| 60.9| 66.7| 66.7| 60.9| 120.9|
| Ver. Estimated  | 89.7| 70.6| 66.4| 101.9| 71.7| 71 | 51.3| 60.9| 75.4|

Figure 10. Estimated MTF at 18 points for OS2. Distance to the test object is 40 mm.
Table 8. The spatial frequencies at 0.5 and 0.1 levels of MTF for OS2 (in mm\(^{-1}\)). Distance to the test object is 40 mm.

| Point’s number | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   |
|----------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| **Left channel** |     |     |     |     |     |     |     |     |     |
| **Level 0.5**   |     |     |     |     |     |     |     |     |     |
| Zemax           | 37.1| 30.3| 28.9| 28.9| 30.3| 37.1| 49.2| 40.3| 38.4|
| Estimated       | 22.8| 33.5| 31.1| 29.1| 29.3| 26.9| 34  | 43.6| 45.6|
| **Level 0.1**   |     |     |     |     |     |     |     |     |     |
| Zemax           | 52.3| 26.5| 17.6| 17.6| 26.5| 52.3| 42  | 26  | 17.7|
| Estimated       | 31.5| 39.8| 24.1| 24.4| 36.6| 22.9| 40.2| 42.4| 23.8|
| **Right channel** |     |     |     |     |     |     |     |     |     |
| **Level 0.5**   |     |     |     |     |     |     |     |     |     |
| Zemax           | 72.7| 64.7| 63.4| 63.4| 64.7| 72.7| 122 | 116.6| 114.3|
| Estimated       | 52.1| 71.7| 59.6| 58.7| 65.7| 58.7| 88.1| 113.5| 100.8|
| **Level 0.1**   |     |     |     |     |     |     |     |     |     |
| Zemax           | 121 | 53.3| 31.1| 31.1| 53.3| 121 | 117 | 52.8 | 31.2|
| Estimated       | 84.8| 82.3| 60.8| 51.6| 83.6| 50.4| 111.1| 83.3 | 53 |
| **Point’s number** | 10  | 11  | 12  | 13  | 14  | 15  | 16  | 17  | 18  |
| **Right channel** |     |     |     |     |     |     |     |     |     |
| **Level 0.5**   |     |     |     |     |     |     |     |     |     |
| Zemax           | 38.4| 40.3| 49.2| 37.1| 30.3| 28.9| 28.9| 30.3 | 37.1|
| Estimated       | 40.7| 42.5| 28.6| 27.3| 34  | 36.8| 28.4| 30.8 | 23.4|
| **Level 0.1**   |     |     |     |     |     |     |     |     |     |
| Zemax           | 17.7| 26  | 42  | 52.3| 26.5| 17.6| 17.6| 26.5 | 52.3|
| Estimated       | 26.8| 37.3| 27.7| 31.8| 33.9| 23.8| 22.8| 28.3 | 23  |
| **Level 0.1**   |     |     |     |     |     |     |     |     |     |
| Zemax           | 114.3| 116.6| 122 | 72.7| 64.7| 63.4| 63.4 | 64.7 | 72.7|
| Estimated       | 94  | 107.5| 78.3| 68.4| 86.1| 71.8| 55.5| 71.2 | 55.2|
| **Estimated**   | 31.2| 52.8| 117 | 121 | 53.3| 31.1| 31.1 | 53.3 | 121|

In order to draw conclusions about the summary quality of the optical system, it is sufficient to compare the figures for OS1 and OS2 at one of the working distances, for example, at 15 mm (figures 6 and 9 for OS1 and OS2, respectively). Figure 9 shows that the experimentally measured MTF differs from the Zemax calculated one by 2-4 times at levels of 0.5 and 0.1. It indicates that OS2 has serious assembly faults. Figure 6 shows the estimated MTF for different areas of the image obtained using OS1. It indicates that the ratio of spatial frequencies for estimated MTFs to spatial frequencies for calculated MTFs at levels of 0.5 and 0.1 is less than 1.5 times. The main reason of that is possible noise distortions, which are not taken into account when estimating the MTF. Therefore this value is acceptable for our solution.

4. Conclusion

In this article, the possibility of using the slanted edge algorithm of MTF measurement for a stereoscopic endoscopic system was considered. It is shown that three images of plane test object with chessboard pattern on different working distances and 9 points of calculation per channel is enough for MTF estimation. A comparison of the estimated MTF with the Zemax calculated ones made it possible to identify assembly faults for the two self-developed prism-based stereoscopic endoscopy systems.

Further work will be directed towards automating the process of the MTF estimation from an image of chessboard pattern and developing user-friendly software for simultaneous spatial calibration and estimation of image quality. Usage of the detection algorithm of nodal points, the description of which can be found in [9], makes possible to select suitable areas for MTF measurements automatically. It allows us to build a map of the MTF values over the entire field of view. Capturing several images at the same position of the test object allows:

1. to evaluate the noise characteristics of the system and their impact on MTF measurements;
2. to reduce MTF measurement error by obtaining an average image over several frames.

Solution of the MTF estimating task allows us to create a universal user-friendly software that allows geometric calibration, measurement of distortion, MTF and noise characteristics. It will provide an opportunity to assess the quality of the operating system not only during assembly and adjustment, but also during the appraisal and working time of the device. Moreover, these procedures will make calibration and quality check available for users of the system without specialized personnel.

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