# ОПТИЧЕСКИЕ И ОПТИКО-ЭЛЕКТРОННЫЕ ПРИБОРЫ И СИСТЕМЫ

DOI: 10.17586/0021-3454-2018-61-3-257-266

# COMPARATIVE ANALYSIS OF RESOLUTION MEASUREMENT METHODS FOR THE OPTOELECTRONIC SYSTEMS

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Machine vision systems are a dynamically developing field of robotics. They give the ability to detect, visualize, track and recognize objects to the manufacturing and controlling cyberphysical systems. The use of such systems along with modern image processing algorithms allows shifting part of the operator's routine duties to a robotic system, in accordance with the industry 4.0 paradigm. An important property of the machine vision system is the resolving power, which can be estimated using various parameters and characteristics. The goal of this paper is to compare existing resolution measurement methods for the machine vision systems and to discuss their advantages and drawbacks.

***Keywords:*** *resolution, machine vision, cyberphysical system, television system, MTF, image quality*

**Introduction.** Machine vision systems are a dynamically developing field of robotics as they give the ability to detect, visualize, track and recognize objects to the manufacturing and controlling cyberphysical systems. Being combined with modern image processing and segmentation algorithms, this allows to bring such systems to a qualitatively new level of decision-making independence and also allows to free the operator from performing routine actions, which is one of the priorities of industry 4.0. Such development of machine vision systems leads to a significant reduction in the cost of production and control processes, and ultimately to the improvement of product quality.

In the course of work on the organization of high-precision automated production, the task of determining the quality of the machine vision system inevitably arises. An important characteristic of the machine vision system, which is in fact television surveillance system, is resolution, which can be estimated using various parameters and characteristics.

As there are a number of methods for the TV systems resolution measurement with varying accuracy, it seems to be important to compare them.

All the existing resolution measurement methods can be subdivided into several groups by the type of the pattern used:

— method using groups of bands of equal width;
— MTF (Modulation Transfer Function) determining by the random target method;
— MTF determining by the laser generated speckle pattern method;
— method for determining the MTF using slanted edge.

It is necessary to clarify that MTF describes spatial frequency response of the imaging system, transferring from the area of objects to the image area using a series of contrast values of sine waves with different spatial frequency [1].

**Method using groups of bands of equal width.** One of the simplest and long used methods is visual method to determine the resolution using test charts including groups of black and white bands having equal width within a single group (Fig.1). Each group usually has the number, indicating the resolution of television optoelectronic system (TOES) in lines (or pairs of lines) per mm.

*Fig. 1*

To determine the resolution of the TOES it is connected to display, having a resolution several times higher than the resolution of the television system, and pointed at test chart. Chart should be fit into the frame using marks at the charts edges. Operator finds the last group, where bands are still individually distinguishable, i.e. the contrast of this group is sufficient. The number near the group defines the resolution of the system.

If it is necessary to determine the resolution more accurate, hyperbolic or straight wedge-shaped pattern can be used instead (Fig.2).

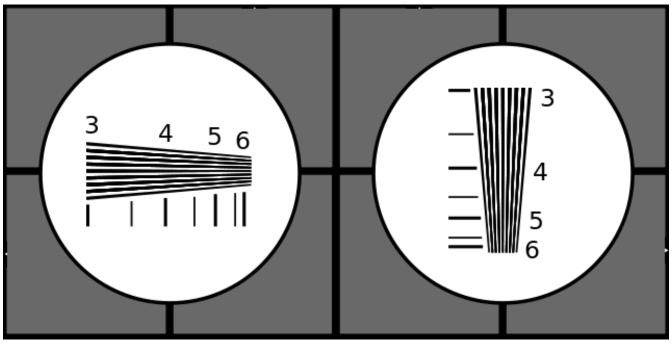

*Fig. 2*

These patterns are included in the existing test charts (e.g. USAF-1951, ISO 12233, IT-72).

To eliminate the human factor during measurement resolution can be determined with oscilloscope, connected to the TOES. Evaluation is made by two adjacent single pulses. The quantitative value of the resolution is the reciprocal of the smallest time interval between the pulses, while they are still could be determined on the display [2] (Fig. 3, where *a* — test pattern, *b* — output signal).

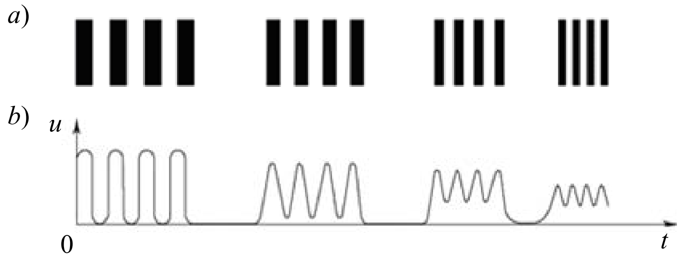

*Fig. 3*

There are more rare types of TOES, e.g. retina-like sensors [3], which sensitive elements are located like photoreceptors in the human retina [4]. For such sensors test patterns can be represented as spoke targets with different periods.

To automate the process of resolution measurement and to increase its accuracy one can compute test pattern spatial frequency spectrum and eliminate background and noise characteristics along the several lines of a sensor [5]. The other way is computing the MTF of the test pattern in the form of groups of equal width bands [6].

Despite the fact, the method using groups of bands of equal width is quite widespread and simple it has drawbacks.

The main disadvantage of the method is that it is complicated to measure resolution of CCD or CMOS based TOES. When using the array of solid-state photodetectors, the final image is deformed by so-called artifacts, caused by the matrix nature of the photodetector. In Fig. 4 the artifacts are visually distinguishable at wedge-shaped pattern, and the signal beats at the waveform indicate the presence of artifacts at the lowest groups of bands. By reducing the number of test pattern bands moiré visibility can also be reduced, however they will be still visible with the amount twice smaller than the amount of photodetectors elements [7]. Fig. 4 shows the moirés observed by the system and the waveform of the lowest groups of bands.

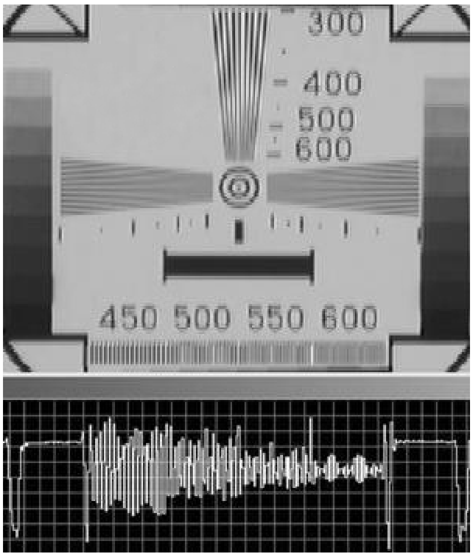

*Fig. 4*

**MTF determining by the random target method.** MTF determining using so-called random target is quite an interesting method of resolution measurement.

The advantages of using MTF as the main characteristic to measure TOES resolution are:

— the ability to measure the quality of the image directly and quantitatively;

— objectivity and flexibility of the measurement (minimal influence of the human factor);

— the ability to measure the quality of the combined systems (various system components, such as the eye, the lens, the photodetector can be reduced to one characteristic) [8, 9].

MTF determining by the random target method represents capturing the test pattern of dots array, which brightness is generated randomly by the random number generator from “zero” (black) to “one” (white) signal level with the required sampling rate (Fig. 5).

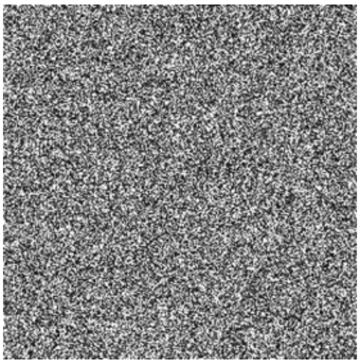

*Fig. 5*

The image received then can be printed on transparent film, illuminated from behind by uniform light source [10, 11], or displayed on the LCD-screen [12].

Modulation transfer function of the TOES ($\mathrm{MTF_s}$) is calculated by the following equation:

$$\mathrm{MTF_s} = \sqrt{\frac{\mathrm{PSD_{out}}}{\mathrm{PSD_{in}}}},$$

where $\mathrm{PSD_{out}}$ and $\mathrm{PSD_{in}}$ are power spectral densities of the output and input test pattern respectively.

PSD value is found by applying a Fast Fourier Transform (FFT) to the image.

This method can be used both for whole TOES MTF determining and for its separate components: photodetector [12] and lens [13].

To improve the accuracy several measurements are done. There are also separate measurements for the set noise and environmental impact determining by measuring TOES MTF using neutral-gray test-image. An example of the algorithm is shown in Fig. 6.

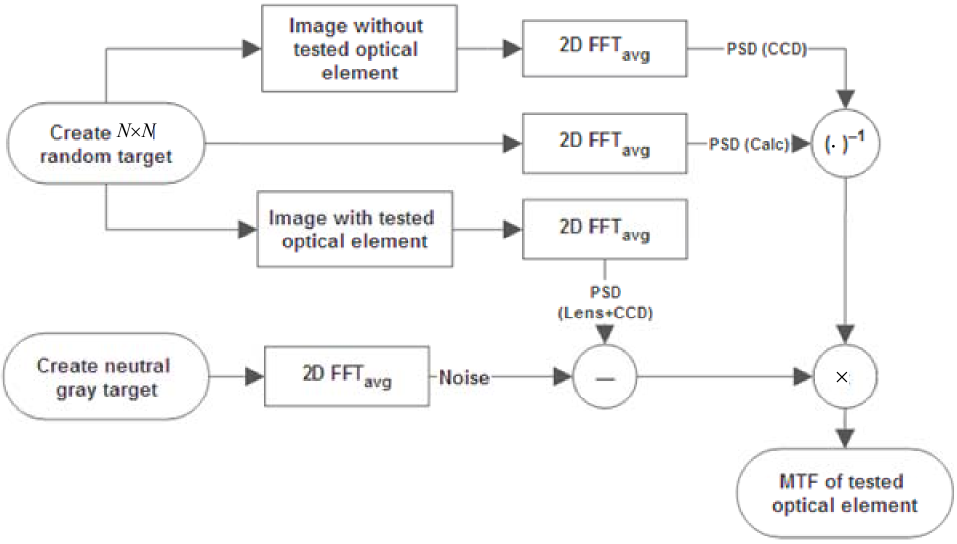

*Fig. 6*

Accuracy of the MTF determining by the random target method is achieved due to two-dimensionality of the test pattern.

Marom et al. proposed MTF determining method by 2D test pattern in 2010 [14]. Authors explained that a 2D pattern differs from a 1-D template as its brightness changes in two orthogonal directions, and the resulting contrast transfer function (CTF) for a 2D pattern will be affected by the brightness changes in another direction, which will not occur when using the 1D pattern. Haim et al. proved theoretically and experimentally that the CTF measured by the 2D pattern is lower than at 1D pattern at every spatial frequency and at its cutoff frequency it is $1/\sqrt{2}$ times lower than the latter one [15, 16].

Liquid-crystal tunable filter (LCTF) is also used when determining TOES MTF using random target image. LCTF is, in fact, bandpass filter, based on LC controllable elements, transmitting one wavelength and cutting off the rest [17]. The filter application allows determining the MTF of the system using quasimonochromatic illumination and makes it possible to characterize it at different wavelengths [18]. There is an experimental setup scheme in Fig.7.

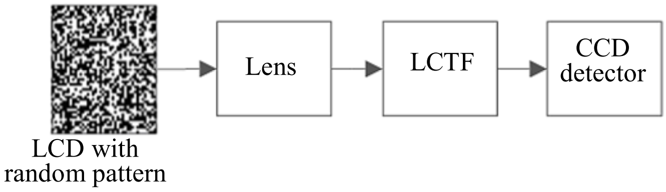

*Fig. 7*

The methods of MTF measurement using random target mentioned above are fast and have high accuracy within the Nyquist frequency. The disadvantages are:

— the complexity of using the method with the high-resolution TOES, which can resolve the separate elements of display;

— the discrete nature of the resulting MTF.

**MTF determining by the laser generated speckle pattern method.** Some drawbacks of the previous method can be corrected by determining the MTF using the speckle pattern (speckle), generated by laser radiation and diffuser.

Speckles is the interference pattern of irregular wave fronts formed by the fall of coherent radiation to the rough surface [19]. One should distinguish objective speckles formed in the space in front of the illuminated surface and subjective, arising when projecting scattering surface image to the photodetector by the optical system, thus subjective picture parameters will depend on the parameters of the optical system.

When generating speckle pattern using integrating sphere there are multiple diffuse reflections of the laser radiation inside it, which produce a field at the exit aperture of the sphere characterized by random phase and uniform brightness. A speckle pattern can be detected after the integrating sphere [20].

MTF determining method using speckle-pattern within the Nyquist frequency was presented by G. Boreman et al. [21] and then improved for frequencies two times higher than the Nyquist frequency [22].

An exemplary experimental setup to determine the CCD array MTF by the speckle pattern consists of He-Ne-laser source, an integrating sphere as a diffuser, a linear polarizer (to get linearly polarized speckle pattern), slit aperture [23] (shape depends on the method used) and the CCD-based camera under study connected to the PC [24]. The laser radiation is directed to the input aperture of the integrating sphere, generating a speckle pattern at the output aperture. The radiation emerging from the output port of the integrating sphere shows uniform irradiance and a uniformly distributed phase (Fig. 8, where A — aperture, P — polarizer). PSD of the final image is then compared with PSD of the pattern at the system input and MTF is calculated by equation being used in random target method.

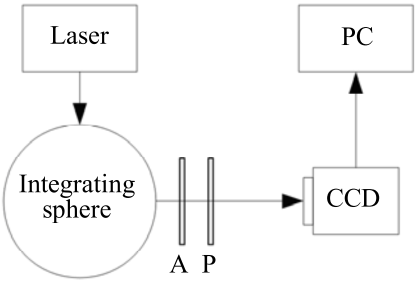

*Fig. 8*

Opal-milk glass may also be used as the diffuser to generate speckle pattern [25]. Chen et al. claim its stability to mechanical vibrations and the big amount of generated random dots.

The method using speckle pattern is quite good to determine the TOES resolution in different parts of the frame. For this purpose, the image field of the TOES should be completely filled by speckle pattern and the FFT is performed separately in different areas of the frame (Fig. 9) [26].

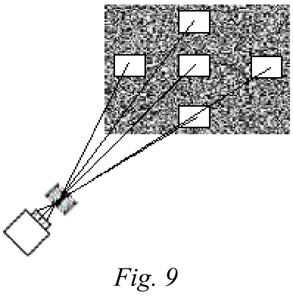

*Fig. 9*

To avoid some possible errors during MTF determining at low- and high-spatial-frequency, Pozo et al. [27] suggest the method implying dark-frame subtraction, usage of two diffusers (rotating and fixed) to generate the speckle pattern and also correction of the distance between aperture and CCD considering the influence of the protective glass. Experimental setup for the measurement of the CCD MTF is shown in Fig. 10, where R is a rotating transmissive diffuser, D is a fixed transmissive diffuser, A is a single-slit aperture, P is a polarizer.

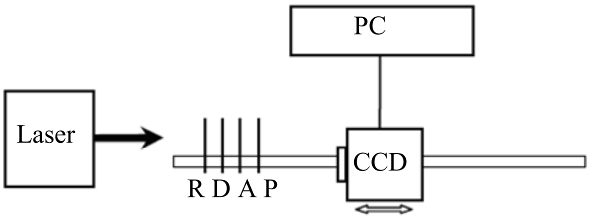

*Fig. 10*

Method of MTF determination using speckle pattern seems to be quite precise and deprived of the main drawbacks of the random target method. The main disadvantage of the method is the relatively high prices and complexity of the setup.

As far as some components of the setup, such as integrating sphere and He-Ne-laser, are quite expensive, some attempts are being made to develop cheaper setup variants [28]. Setup scheme is similar to the one in Fig. 8, however the laser diode is used instead of He-Ne-laser, ping-pong ball replaces the integrating sphere and high quality slit aperture is replaced by the cardboard one.

The results of the experiments described in the article [28] shows that MTF function is almost independent on the quality of setup components.

**Method for determining the MTF and spatial frequency response using slanted edge.** Method for determining the modulation transfer function using a sloping edge, or spatial frequency response (SFR), as described in standard ISO 12233, is one of the most common and currently most widely represented in the literature [29—31]. The method was originally designed to determine the resolution of still-image cameras, but also works for any TOES with the ability to record images or video stream.

Basic algorithm of the method for MTF measurement is shown in Fig. 11 [32].

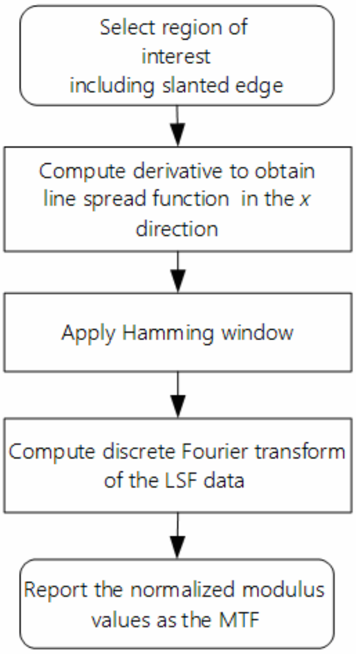

*Fig. 11*

This method is not affected by the moiré inherent to the visual method [33], it has high accuracy in the range of the Nyquist frequency, and applicable to a wide range of TOES: it is used in radiography [34, 35], tomography [36], and in fluorescent image technique [37]. Machine vision is also a perspective area for the method [38].

The method accuracy depends on several factors. The slanted edge tilt angle seems to be quite important as at angles (α) more than 5 degrees MTF value decreases quite rapidly [39] (Fig. 12).

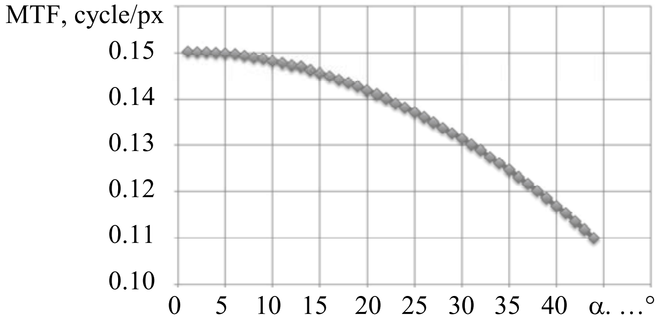

*Fig. 12*

The contrast of a slanted edge to the background is not so important in the absence of noise, but in their presence, too low contrast edge may not be visible by the receiver. To solve the problem of noise impact when using slanted edge, one can use different low pass filters [40] as far as modified multidirectional slanted edges having improved noise resistance [41].

This method also has some disadvantages. Among them are possible errors when analyzing the color cameras [42], which can be solved however by making some changes in the demosaicing algorithm. The second one is dependence of the method accuracy on printing quality of the test pattern [43]. It can be solved by using high definition printers or by using optical schemes with metal slanted edge [44], which makes measurement process more complicated, on the other hand.

**Conclusion.** The main methods to determine resolution of television systems were discussed and their comparative analysis was made to choose the most suitable one applied to the tasks of analyzing radiation-tolerant television systems. Advantages and drawbacks of the methods are summarized in Table.

| Method | Advantages | Disadvantages |
|---|---|---|
| Method using groups of bands of equal width | Relative ease of application.<br>Low cost of test bench.<br>Proven and “time-tested” techniques | Moirés at the test pattern when using solid-state array photodetectors, which make the resolution determining more complicated.<br>Human factor |
| MTF determining by the random target method | High accuracy of determining resolution of the television systems within the Nyquist frequency.<br>No need to print the test-pattern.<br>Possibility of fast changing of test-pattern parameters | Complexity of using the method with the high-resolution TOES, which can resolve the separate elements of display.<br>Discrete nature of the resulting MTF |
| MTF determining by the laser generated speckle pattern method | High accuracy (making measurements at frequencies exceeding Nyquist frequency is possible).<br>Possibility of changing test-pattern parameters.<br>Possibility of making measurements at different wave lengths, including infrared spectral region | Relative complexity and expensiveness of the setup.<br>Complexity of making reference channel |
| Method for determining the MTF and spatial frequency response using slanted edge | High accuracy within the Nyquist frequency.<br>Suitable for a wide range of TOES.<br>Relatively easy application | Possible errors when analyzing the color cameras.<br>Dependence on printing quality of the test pattern |

Considering the review and comparative analysis of existing methods of determining television systems resolutions as well as advantages and disadvantages of these methods we can assume that to analyze television systems we need to develop the unified method which allows estimating television system resolution for different frame areas and in two directions (horizontal and vertical). The method should use two-dimensional test pattern or group of test patterns, which are associated with point scattering.

This work was supported by the RF Ministry of Education and Science (RF Government resolution № 218, April 9, 2010 (R&D project N 03.G25.31.0251 dated April 28, 2017 at ITMO University "Creation of high-tech production of configurable frequency converters for new generation of synchronous precision high-speed high-power electromechanical drives").

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Received
11.10.17

**For citation**: Perezyabov O. A., Maltseva N. K., Ilinski A. V. Comparative analysis of resolution measurement methods for the optoelectronic systems. *Journal of Instrument Engineering*. 2018. Vol. 61, N 3. P. 257—266 (in English).

## СРАВНИТЕЛЬНЫЙ АНАЛИЗ МЕТОДОВ ОПРЕДЕЛЕНИЯ РАЗРЕШАЮЩЕЙ СПОСОБНОСТИ ТЕЛЕВИЗИОННЫХ ОПТИКО-ЭЛЕКТРОННЫХ СИСТЕМ

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Рассматривается такая динамично развивающаяся область робототехники, как системы машинного зрения, позволяющие производственным и контролирующим киберфизическим системам обеспечить возможность обнаружения, визуализации, отслеживания и распознавания объектов. Использование подобных систем с современными алгоритмами обработки изображения позволяет переложить часть рутинных обязанностей оператора на робототехническую систему, в соответствии с парадигмой индустрии 4.0. Важным свойством системы машинного зрения является разрешающая способность, которую можно оценить при помощи различных параметров и характеристик. Представлен сравнительный анализ существующих методов измерения разрешающей способности оптоэлектронных систем и определены их преимущества и недостатки.

**Ключевые слова:** разрешающая способность, машинное время, киберфизические системы, телевизионные системы, функция передачи модуляции, качество изображения

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**Ссылка для цитирования:** *Перезябов О. А., Мальцева Н. К., Ильинский А. В.* Сравнительный анализ методов определения разрешающей способности телевизионных оптико-электронных систем // Изв. вузов. Приборостроение. 2018. Т. 61, № 3. С. 257—266.

DOI: 10.17586/0021-3454-2018-61-3-257-266