Методы и средства обработки сигналов и изображений

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About modulation transfer function of machine vision system based on CMOS and CCD image sensors

In the process of designing a machine vision system, a critical step is selecting an image sensor and optics that satisfy required parameters of resolution. The resolution of the image sensor is determined by modulation transfer function (MTF). In this paper a method for the theoretical estimation of MTF based on topologic parameters of the image sensor and parameters of lenses is proposed. The purpose of this work is development a method that will be handy instrument for the resolution calculation of the imaging system on the initial stage of the designing process of the machine vision. In this paper dependency of MTF for different parameters of image sensor and lenses were presented. This method can be used for calculation resolution of imaging system in object's plain domain. References 7, figures 3, tables1.

Keywords: *modulation transfer function (MTF), machine vision system (MVS), point spread function (PSF), image sensors, modeling, spatial frequencies.*

Introduction

Nowadays, CMOS and CCD image sensors are widely used as imaging systems in machine vision systems (MVS). The main advantage of these integral image sensors is the possibility to create an ordered optoelectronic set of elements with parallel-serial processing of visual information on a chip. CMOS and CCD image sensors perform the function of converting a spatially distributed input optical signal into an output electrical video signal [5].

The main demands set to the MVS parameters are related to accuracy of flow detection and time performance, such as frame rate, exposure time etc. The choice of the image sensor influences both of these criteria and also it influences the selection of the hardware platform, optics and the frame grabber. Thus, one of the first-priority tasks in the process of designing machine vision is selection of image sensor. One of the main parameters of the machine vision systems is resolution, it‘s determined precisely by image sensor. This characteristic shows ability of the imaging system to render fine image structures. However in documentation to image sensor resolution is not mentioned, it's caused by strong dependency of this performance from parameters of lenses, environment and image sensor modes. Thus, in most cases for the resolution estimation is used the physical prototyping of imaging system, which leads to extra spending and increasing of designing time of machine vision. This work is aimed to make handy instrument that can be used for the resolution calculation of the imaging system on the initial stage of the designing process of machine vision.

Resolution or spatial filtration of optical signals is determined by the modulation transfer function (MTF), which shows the resolution (line pairs to one mm) of the system for the given level of contrast. Nowadays different analytical models for MTF evaluation have been presented. They can be divided into two categories: the first one are based on defining a continuity equation for monitory carriers flow [1,4,6], the second one on the implementation the Fourier transformation to the approximated impulse response function of a pixel [2,7,8]. In the case of first, the models are distinguishable by their complexity and they are almost entirely based on topological parameters of image sensors and parameters of photo-generated carriers diffusion (e.g. diffusion coefficient, doping concentration, diffusion length etc.). These models give a good level of accuracy, but they are difficult in use because these models utilize special parameters that are known only by vendors of image sensors. Second category is based on parameters of image sensor pixel shape, which is also unmentioned in image sensor datasheet. All this methods are designed for the implementation in the process of designing image sensor chip structures as a tool for the preliminary analysis of performance of different pixel shapes.

The method proposed in this article can be included in the second category, but it is based exclusively on the parameters of the image sensor specified in a datasheet and aimed to improve accuracy and reduce time spent on the designing processes of machine vision systems.

1. Spatial filtration of the optical signal in the imaging system

The smallest element of optical image decomposition in the case of an image sensor is the pixel of photosensitive array. All pixels of the image sensor are equal by their topological and electronic parameters and carry out the same function of optical signals conversion. From this viewpoint the image sensor can be considered as a linear space invariant system, so we can define a modulation transfer function of image sensor as Fourier transform of an impulse response to the point light source [2].

To evaluate the impulse response, we have to take into account factors cause spatial filtration of the optical signal in imaging systems. There are two main reasons of decrease of the modulation depth with increase of the spatial frequency:

1. Spatial averaging of object projections by finite sizes of pixel area. Photon flux that irradiates the pixel is averaged over its area. So the output signal of the pixel will not look like a light "pattern”, which was projected onto the pixel, but will look like an averaged gray level. (Fig.1). We assume that sensitivity across the entire surface of the pixel is equal, and it is specified by a rectangular sensitivity function [3]:

$$S(\mathrm{x}) = \begin{cases} 1, |x| \le \Delta x / 2, \\ 0, |x| \le \Delta x / 2. \end{cases} \quad (1)$$

where Δx - pixel size.

2. Diffraction of the optical system. Light coming from a point light source diffracts through the lens aperture such that it forms a diffraction pattern. This effect can be described by a point spread function (PSF), which can be fitted by a sinc function:

$$P(\mathrm{x}) = \left(\frac{\sin(\pi \mathrm{x})}{\pi x}\right)^2 \quad (2)$$

Since in most image sensors is used raster scan, which means that line scan rate considerably higher that frame rate, without loss of accuracy the one dimensional case in horizontal direction will be considered.

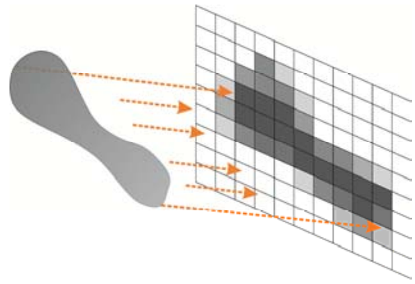

Fig. 1. Principle of decomposition of optical image by image sensor [5]

The impulse response of an image sensor pixel K(x) to the point light source is calculated as the result of the convolution of S(x) and P(x) functions. It should be noted that we consider an image sensor and lenses as a united, inseparable electro-optical system.

To fit a characteristic of the diffraction of a real objective by P(x) function we have to calculate the radius of the first maximum of the PSF, which is called an Airy disk. It is calculated by the formula [8]:

$$r = 1{,}22((\lambda\, \mathrm{f}) / \mathrm{d})\ [\mathrm{mm}] \quad (3)$$

where λ - irradiance wavelength; f/d - f-number, f - is focal length and d is diameter of the aperture;

According to properties of the sinc function we enter coefficient r in an argument. Then the PSF from point light source in sensor plane will be:

$$P(\mathrm{x}) = \left(\frac{\sin(\pi \mathrm{x} / \mathrm{r})}{\pi x / r}\right)^2 \quad (4)$$

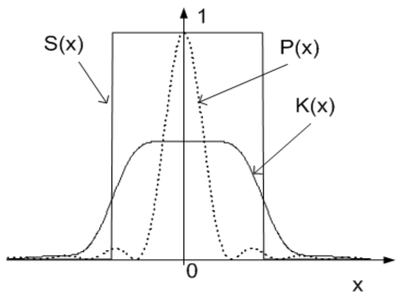

Fig. 2. The determination of the impulse response function of the imaging system K(x)

Then impulse response function of imaging system will be:

$$K(\mathrm{x}) = \int_{-\infty}^{+\infty} S(\mathrm{x}-\mathrm{y})(\sin(\mathrm{y}\,\pi) / (\mathrm{y}\,\pi))^2 dy \quad (5)$$

2. Evaluation of the MTF

Considering the response of the image sensor to a point light source projected through the lens as the impulse response function, we move through the Fourier transform of this function to the MTF of an imaging system.

Normalized MTF of an electro-optical system [8]:

$$MTF(\omega_x)=\left(\int_{-\infty}^{\infty}K(x)e^{-i\omega_x x}\,dx\right)/\left(\int_{-\infty}^{\infty}K(x)dx\right) \quad (6)$$

where ω_x is a spatial frequency;

2.1. A scale factor

In the process of designing a machine vision system an engineer needs to know the resolution in an object scene plane domain, because this actually shows the ability of machine vision to “see” or not a defect or a part. The transfer from spatial frequencies in plane of image sensor to spatial frequencies in plane of field of view is obtained using scale factor.

A scale factor shows the degree of an optical image compression. It is a ratio of an object size to an image size (Fig.3), or a field of view of the imaging system to a size of effective area of the image sensor [3]:

$$\beta=\frac{y}{y'}=\frac{\textit{field of view}}{\textit{sensor size}} \quad (7)$$

Considering β MTF is evaluated as:

$$MTF(\omega_x)=\left(\int_{-\infty}^{\infty}K(x)e^{-i\beta\omega_x x}\,dx\right)/\left(\int_{-\infty}^{\infty}K(x)dx\right) \quad (8)$$

Results

Using this method MTF of imaging system for two boundary values of the aperture diameter f/1,4 f/16 was determined. For better observation graphics were built for two image sensors with equal sizes, but different pixel sizes 6 um and 4 um. This means that the image senor with smaller pixels has better camera resolution, i. e. more pixels. The parameters used for розрахунку are listed in table 1.

Table 1. Parameters of imaging systems

	Pixel size	Sensor format	β	λ	f-number
Imag. system 1	6 um	1/2 inch	30	550 nm	f/1,4, f/22
Imag. system 2	4 um	1/2 inch	30	550 nm	f/1,4, f/22

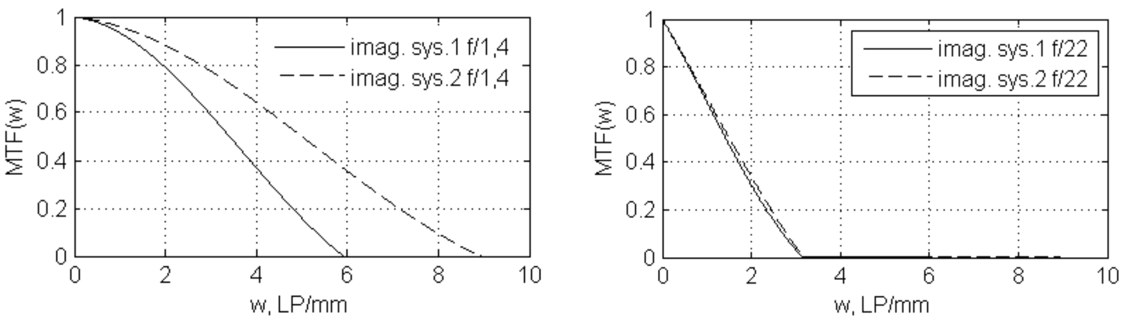

Fig. 3. The MTF of the imaging systems for f/1,4 and f/22:the imaging system 1 – 6 um pixel;the imaging system 2 – 4 um pixel

On the fig. 3 is shown MTF dependency for the imaging systems with spatial frequency (lain pairs per mm) in the object’s plane domain. As can be seen on the first graph of fig.3 for f/1,4, image sensor with a larger number of pixels has a higher resolution which corresponds to the reality. At the graph for f/22 can be seen that the resolution of the systems appreciably decreases, this can be explained by the increasing influence of the diffraction in diaphragm aperture. Also it can be seen that the MTF of systems with 4um and 6um is practically equal. For the small size aperture the diameter of the Airy disk became bigger than the pixel area and diffraction effect prevails over the other factors that determine the resolution.

Conclusion

In this paper a method of determining MTF of imaging systems based on CMOS and CCD image sensors has been considered. It is based on topological parameters of image sensors, parameters of the optical system and image sensor modes. The main idea lies in considering the image sensor and lens as a unified system. This allows us to receive the modulation transfer function of an imaging system as the Fourier transform from an impulse response function. An impulse response function is evaluated from the convolution of the PSF of objective and the pixel sensitivity function. This closely corresponds to physical processes that cause a spatial filtration of an optical signal.

Utilization of this method enables to appraise the resolution of the machine vision system without physical prototyping of imaging system on the initial stage of the designing process of machine vision. This can significantly reduce time and resources spent on the design stage of machine vision systems based on CMOS and CCD image sensors. Based on this model we can select the image sensor that perfectly supplies requirements of the specified application field of machine vision. Fair important for machine vision is the fact, that in this method, we receive MTF in the object of view plane domain.

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Про контрастно-частотну характеристику системи технічного зору, побудованої на КМОН- і ПЗЗ сенсорах зображення

У процесі проектування системи технічного зору (СТЗ) , важливим кроком є вибір сенсора зображення і об'єктива, які б задовольняли поставленим вимогам до роздільної здатності . Роздільна здатність датчика зображення визначається по частотно-контрастній характеристиці (ЧКХ). У даній роботі запропоновано новий метод теоретичної оцінки ЧКХ , який базується на топологічних параметрах сенсора зображення і параметрах об'єктива. Мета цього методу полягає у створенні зручного інструменту для попереднього визначення роздільної здатності системи формування зображень на ранніх етапах проектування системи технічного зору. Основна ідея методу полягає в розгляді сенсора зображення з позиції вихідного сигналу сенсора і параметрів, що впливають на нього, таких як, параметри освітленості, оптичної системи, сенсора зображення. У даній роботі була представлена залежність ЧКХ для різних параметрів сенсора зображення і об'єктива. Цей метод дозволяє розрахувати роздільну здатність системи формування зображення в площині досліджуваного об'єкта, що значно *підвищує інформативність даної характеристики в сенсі проектування СТЗ .* Бібл. 7, рис. 3, табл.1.

Ключові слова: *частотно-контрастна характеристика (ЧКХ) , функція розсіювання точки (ФРТ) , сенсор зображення , моделювання; просторова частота.*

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О частотно-контрастной характеристике системы технического зрения, построенной на КМОП-и ПЗС- сенсорах изображения

В процессе проектирования системы технического зрения (СТЗ), важным шагом является выбор сенсора изображения и объектива, которые бы удовлетворяли требованиям, поставленным к разрешающей способности. Разрешение датчика изображения определяется по частотно-контрастной характеристике (ЧКХ). В данной работе предложен новый метод теоретической оценки ЧКХ, который основан на топологических параметрах сенсора изображения и параметрах объектива. Цель этого метода состоит в создании удобного инструмента для предварительного анализа разрешающей способности системы формирования изображения на ранних этапах проектирования системы технического зрения. Основная идея метода заключается в рассмотрении сенсора изображения с позиции выходного сигнала сенсора и параметров влияющих на него, таких как, параметры освещенности, оптической системы, сенсора изображения. В данной работе была представлена зависимость ЧКХ для различных параметров сенсора изображения и объектива. Этот метод позволяет рассчитать разрешающую способность системы формирования изображения в плоскости объекта, что значительно повышает информативность данной характеристики в смысле проектирования СТЗ. Библ. 7, рис. 3, табл.1.

Ключевые слова: *частотно-контрастная характеристика (ЧКХ), функция рассеяния точки (ФРТ), сенсор изображения, моделирование; пространственная частота.*

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