Modeling of Imaging Systems in Matlab

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Abstract. *For many applications in image processing it is necessary to know model of imaging system, which has been used for image data obtain. Knowledge about system can be used for the simulation of an image data in astronomy (telescope and CCD camera, for example in near IR band) or we can treat the compression algorithm as any other imaging system and perform objective image quality measurement.*

Keywords

Image system, modulation transfer function, point spread function, CCD.

1. Introduction

The major part of an imaging system consists of an input opto-electrical converter (optic and sensor), transmission of data (compression) and an electro-optical converter (CRT monitor, LCD display). In this paper the imaging sensor modeling and treating of compression methods is described as an imaging system (measuring of objective image quality).

The common factors in simulation (modeling) of parts of imaging systems are an imaging system transfer characteristics: Modulation Transfer Function (MTF), Point Spread Function (PSF) and Optical Transfer Function. The first part of the paper is dedicated to the transfer characteristics and to relationships between those characteristics, the second part of the paper is dedicated to the particular parts of the imaging systems simulation.

2. Transfer Characteristics

In a standard imaging approach we describe an imaging system by the PSF or the MTF. We can define the response of the imaging system to a point light source (2D Dirac impulse) as the impulse response or the Point Spread Function (PSF). The PSF is frequently used to characterize e.g. the optical blur. The relationship of the imaged object and the original is given by the convolution of the original object with PSF.

$$f_i(x,y) = f_o(x,y) * h(x,y), \tag{1}$$

$$f_i(u,v) = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} f_o(x,y).h(u-x,v-y)\,dxdy, \tag{2}$$

where f_i is an image on the output of the imaging system and f_o is an object on the input of the imaging system, symbol * is convolution.

In the frequency domain, based on the rules of Fourier transform, the convolution becomes a product.

$$\Im\{f_i(x,y)\} = \Im\{f_o(x,y)\}.\Im\{h(x,y)\}, \tag{3}$$

where $\Im$ means Fourier transform.

The Fourier transform of the PSF is known as the Optical Transfer Function (OTF):

$$\Im\{h(x,y)\} = OTF, \tag{4}$$

$$OTF(u,v) = MTF(u,v).e^{j.PTF(u,v)}. \tag{5}$$

The OTF is generally complex and thus it has a module (absolute value) and argument. The module OTF is called the Modulation Transfer Function MTF or Contrast Transfer Function CTF related to contrast. The argument is called the Phase Transfer Function related to frequency shifts. There is an important assumption that the imaging system is linear and both arbitrary input and output can be given by harmonic series with different spatial frequencies.

We can also define so called "contrast" C that helps to describe the contrast transfer efficiency by MTF with respect to spatial frequencies where B is brightness of object and its image:

$$C = \frac{B_{o\max} - B_{o\min}}{B_{i\max} + B_{i\min}}, \tag{6}$$

where $B_{o\ max}$ and $B_{i\ max}$ are maximal brightness of input object and output image and $B_{o\ min}$ and $B_{i\ min}$ are minimal brightness of input object and output image.

All the parts of imaging systems, i.e. atmosphere, objective, image sensor, image processing (including image compression methods as well), image display and finally the observer's eye can be described by MTF. The MTF of the whole imaging system based on the above-mentioned equations is given by the product of all particular MTFs:

$$MTF_{sys} = MTF_{sens+opt}.MTF_{tran}.MTF_{disp}, \tag{7}$$

where MTF_{sys} is MTF of an imaging system, $MTF_{sens+opt}$ is

MTF of an image capture system (for example image part and CCD sensor) and MTF_{disp} is MTF of display.

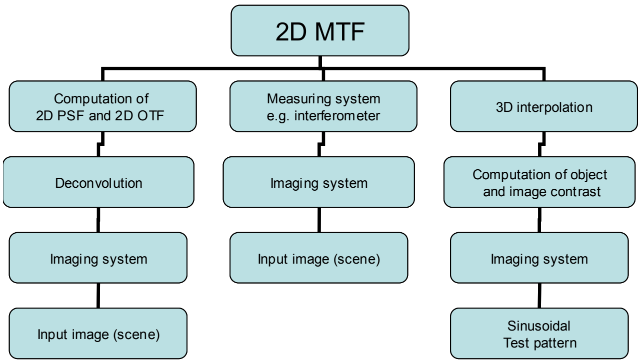

Fig. 1. Three possible approaches concerning with the obtaining of two-dimensional MTF

There are several approaches how to obtain the Modulation Transfer Function of imaging system (see Fig.1.). The first approach is based on restoration methods, including deconvolution. Within these methods we use only image data and computational workstation. The second approach uses specialized measuring system, e.g. interferometer that enables to obtain 2D MTF. This method, however, is exacting in cost. The third approach is our approach requiring to perform a set of 1D MTF (in a lot of angles) computational based on the contrast evaluation within the sinusoidal test pattern projection onto the imaging system. Then we can perform 3D interpolation to obtain a complete 2D MTF. This last approach was implemented in Matlab and used within the obtaining results.

3. Imaging Sensor

There are many parameters of imaging sensors and only a part of them has real impact to consequential image and its quality. For simulation purposes, the interesting parameters are fill factor, sampling distances, dimensions of pixels and area sensitivity of pixels.

The main aim of this section is the process of spatial sampling. On the basis of theory of sampling, known from electrical engineering, we can state that real sampling model of (CCD) structure is represented by the equation:

$$f_i[m,n] = \left(f_o(x,y) * a(x,y)\right) \cdot \sum_{m=-\infty}^{m=+\infty} \sum_{n=-\infty}^{n=+\infty} \delta(x - mX, y - nY) \quad (8)$$

where $f_o(x,y)$ is an input image (object) and $a(x,y)$ is a finite sampling aperture with different distribution over the sampling aperture area (X and Y are sampling distances – distances between the center of active parts of sensor, pixels). The sampling distances are used in accordance with the assignment.

We can consider a few possible arrangement of sampling aperture: rectangular pixels, L-shaped pixels and symmetrical octagonal pixels (Fig. 2, 3, 4). The results obtained with Matlab package *CCDSIM* are presented.

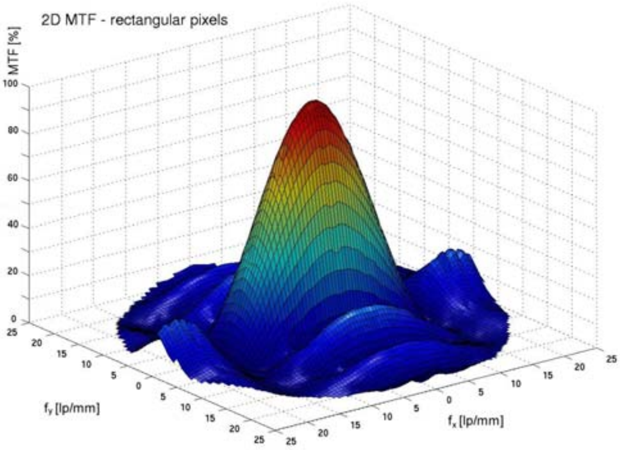

Fig. 2. 2D MTF of sensor with rectangular pixels

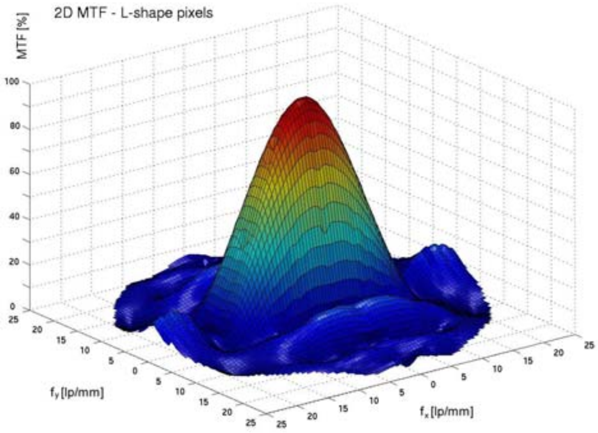

Fig. 3. 2D MTF of sensor with L-shape pixels

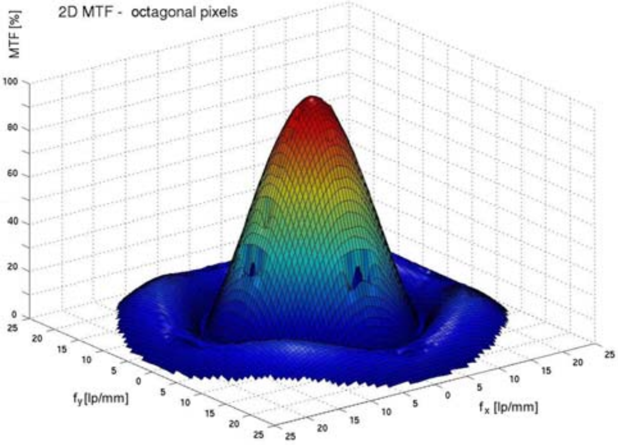

Fig. 4. 2D MTF for sensor with symmetric octagonal pixels

4. Compression Method

In our experiments in objective image quality measurement, we try to measure Modulation Transfer Function of selected image compression methods. As an example we have selected some of the compression methods based on Discrete cosine transform, Hadamard transformation, Karhunen - Loève transform (we have used universal KLT basis determined from the class of astronomical images of DEEP sky kind - it is important that KLT basis was not created from 2D sine image because of its high value of correlation), vector quantization and fractals.

For simulation, we have used unified input image (Fig. 5), coded by selected compressions methods (size of image *1536x1024x16* bits). The methods have had comparable:

- block size *32x32* pixels for DCT, Karhunen - Loève transform, Hadamard transform and vector quantization,
- quantization depth of spectral coefficients *64* bits for DCT, Hadamard transform and fractal transform; *12* bits for Karhunen - Loève transform,
- linear characteristic of quantization block with coefficients equal to 1 or 0 only,
- for fractal encoder S_B, O_B are offset bit parameters.

The method similar to the simulation of transfer characteristics of an imaging system has been used for the obtaining of transfer characteristics of compression methods. The input image (see Fig. 5.) has been compressed with a compression method (KLT and vector quantizer were realized in Matlab), parsed to particular frequency beams and for all beams Modulation Transfer Function has been calculated. The simulation for various angles of input image (sinusoidal pattern) has been performed as an imaging sensor simulation, but the results weren't depending on angle input pattern.

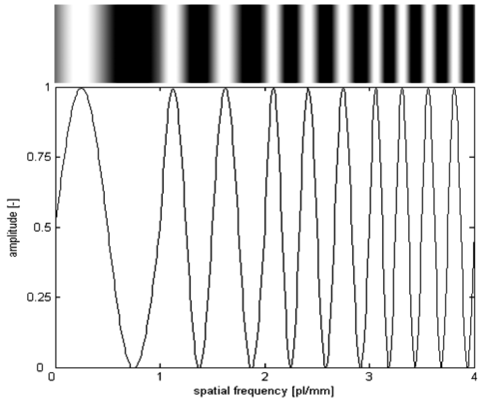

Fig. 5. Testing image with sine profile of grayscale

The following dependencies (see Fig. 6.) were calculated within Matlab in order to demonstrate the above-mentioned objective characteristics for the above-mentioned compression methods. The PSF and MTF characteristics can be used in linear system only.

5. Conclusions

The modeling of the imaging systems in Matlab environment is a full featured, flexible and low cost allowance of traditional measurement methods. The results presented in this paper have been used for the objective (compression methods) and the subjective (model of imaging sensor has been used for obtaining of degraded images) image quality measurement. The Matlab package *CCDSIM*, used for obtaining of the presented results, has been used for education at the Dept. of Radioelectronics, CTU FEE.

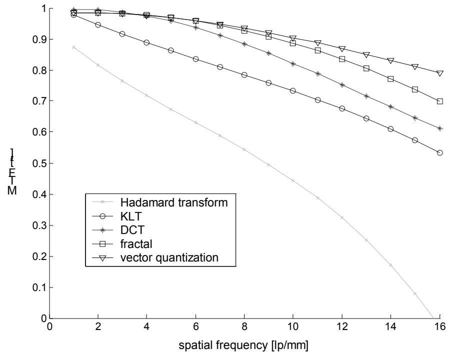

Fig. 6. Modulation transfer function (MTF) of selected compression methods kernels

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References

[1] HOLST, G.C. *CCD arrays, Cameras and Displays.* 2nd ed. Bellingham: SPIE Press, 1998.

[2] YALID-PECHT Geometrical MTF for Different Pixel Active Area Shapes. *Optical Engineering*, 2000, *34*, p. 859 - 865.

[3] VÍTEK, S., HOZMAN J. Image Quality Influenced by Selected Image Sensor Parameters. In *Photonics Prague.* Prague, 2002, p. 167

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