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Analysis of influence of black matrix effect in spatial light modulator on optical correlation detection

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ABSTRACT

Motion detection with a joint transform optical correlator is based on the maximally correlated bright spots in a correlation image; therefore, the quality of a correlation image greatly influences optical correlation detection. As the core component of a joint transform optical correlator, a spatial light modulator has an opaque part (black matrix structure) that is an important factor that needs to be considered. In this paper, we first analyzed the effect of the fill factor on the light energy distribution in the image plane according to the mechanism of the spatial light modulator using a multiple-subpixel matrix to simulate a single pixel, while zeroing some subpixels to simulate the black matrix part in the single pixel and employing computer software to simulate the joint transform optical correlator to obtain the simulated correlation image result with a black matrix effect. In addition, we built an experimental setup to obtain an actually photographed correlation image, which was well consistent with the simulated result.

1. Introduction

Since Jutamulia propounded adoption of a joint transform optical correlator to detect a displacement vector between images in 1992 [1], optical correlators have been widely used for target recognition, detection of small objects, etc. The detection accuracy of an optical correlator depends upon the parameters and types of various key components. Janschek et al., from the Dresden University of Technology, Germany, analyzed the influence of mechanical deformation, the spatial discrete structure of a spatial light modulator (SLM) and a charge coupled device (CCD) camera, noise, the size of an overlay area between a reference frame image and a target image, and geometric deformation of an image on the detection accuracy [2], and also analyzed the effect of inclination and rotation of a Fourier lens and an image sensor, and motion of a light source and image sensor in the longitudinal and horizontal axes on the displacement vector detection accuracy [3]. However, Janschek did not conduct detailed quantitative analysis of the influence of the discrete structure of an SLM on detection accuracy.

A spatial light modulator is a 1D linear array or a 2D array comprised of many basic, discrete, and independent small cells that can independently receive an optical or electrical input signal and can utilize various physical effects to change their own optical characteristics, such as phase, amplitude, intensity, frequency, and polarization, so as to realize spatial modulation or transformation of input optical waves. Owing to the inherent circuit structure in the pixel structure of an electrical addressing spatial light modulator, there are interinsulated column electrodes between the pixels, there are thin film transistors (TFTs) at the intersections of the row and column electrodes, which are built using large scale integration technology, and a row electrode, a column electrode, and a display pixel are connected to the gate, source, and drain electrodes of a TFT, respectively. Light projected to the row and column electrodes causes circuit noise due to the photoelectric effect, so the row and column electrodes are plated with a layer of opaque metal with a light amplitude transmittance of 0. Thus, only a 2D black matrix is generated, and it is composed of two interperpendicular periodic rectangular gratings [4].

The 2D black matrices suppress the circuit noise generated from the photoelectric effect; however, they reduce light utilizing efficiency and introduce multistage diffraction images arranged in arrays, which greatly impact the quality of the generated optical data field and lead to extreme inconvenience for the following optical path or circuit processing. This is the so-called black matrix effect [5].

In this paper, we analyzed the effect of the fill factor on the light energy distribution in the image plane, and employed computer software to simulate the joint transform optical correlator to obtain theoretical correlation images with and without the black matrix effect. We found that the influence of the black matrix effect was well consistent with the actual test result.

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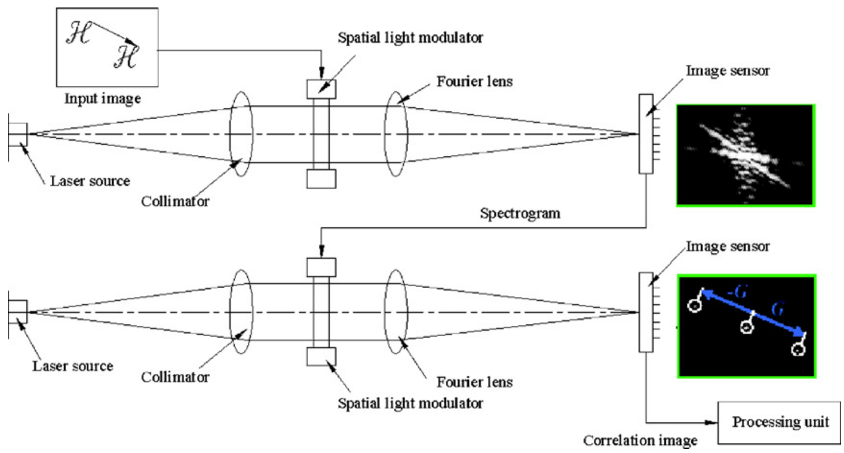

Fig. 1. Schematic diagram of displacement vector detection with an optical correlator.

2. Principle of displacement vector detection with an optical correlator

The principle of displacement vector detection with an optical correlator is as shown in Fig. 1. Two frames of an image, having some relative displacement, are simultaneously inputted into the first spatial light modulator and radiated with a collimated laser beam, and the laser radiated images pass through a Fourier lens to generate spectrograms thereof in an image sensor. The spectrograms are inputted into the second spatial light modulator and radiated by another collimated laser beam, and a correlation image between these two images can be obtained in another image sensor. The correlation image at this time is shown as two maximally correlated bright spots, of which the distance there between reflects the displacement between these two images.

When the system operates, it takes the image at a current time point t from the image sequence as a reference frame and the image at a next time point $t+1$ as an input frame, and simultaneously and symmetrically inputs them into a spatial light modulator such that the motion information from the time point t to the time point $t+1$ is represented by the distance between the bright spots in the correlation image. Thereafter, the reference frame is updated as an image at the time point $t+1$ and the input frame as an image at the time point $t+2$ such that the displacement from the time point $t+1$ to the time point $t+2$ can be known from the distance between the bright spots in the correlation image. The images are updated constantly, and thus the motion information contained in the whole image sequence can be obtained.

3. Theoretical analysis of black matrix effect

The grating structure of a spatial light modulator is as shown in Fig. 2. White indicates transparent or non-zero-reflectivity parts, and black indicates opaque or zero-reflectivity parts.

When it is assumed that the image to be inputted into the spatial light modulator for modulation is $f(x, y)$, that the spaces between two adjacent pixels in the spatial light modulator in the directions of x and y are K and L, respectively, and that the lengths of an opening for valid pass-through of a pixel are a and b in the directions of x and y, respectively, the transmission coefficient of the spatial light modulator is given as

$$t(x,y) = \left[\frac{1}{KL} rect\left(\frac{x}{a},\frac{y}{b}\right) \times comb\left(\frac{x}{K},\frac{y}{L}\right)\right] rect\left(\frac{x}{W},\frac{y}{H}\right)$$

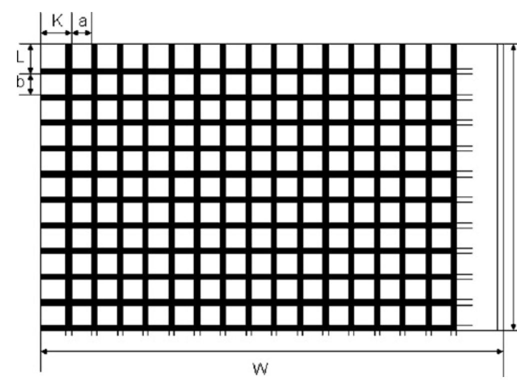

Fig. 2. Structure of SLM.

and the transfer function is given as

$$\begin{aligned} T(u,v) &= of^{-1}\{t(x,y)\} = \frac{ab}{KL}\sin c(au)\sin c(bv) KLcomb(ku, Lv) \\ &\quad \times (WH \sin c(Wu)\sin c(Hv)) \\ &= \frac{ab}{KL}\sin c(au)\sin c(bv)\sum_{n=0}^{E}\sum_{m=0}^{F}\left(u-\frac{n}{K}, v-\frac{m}{L}\right) \\ &\quad \times [WH\sin c(Wu)\sin c(Hv)] = \frac{ab}{KL}\sum_{n=0}^{E}\sum_{m=0}^{F}\sin c(au)\sin c(bv) \\ &\quad WH\sin c\left[W\left(u-\frac{n}{K}\right)\right]\sin c\left[H\left(v-\frac{m}{L}\right)\right] \end{aligned}$$

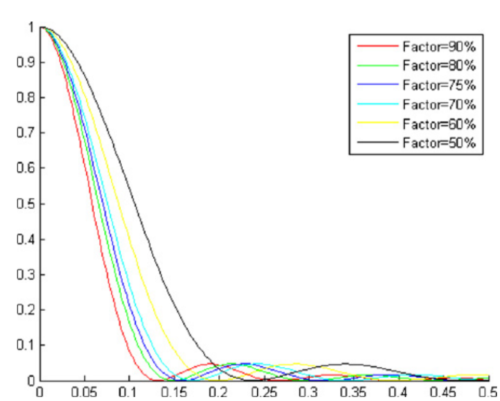

Fig. 3. Intensity distribution corresponding to different fill factors.