Diffraction gratings analysis used in lensless camera technology

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Abstract. We give diffraction gratings an analysis in the lensless camera's construction, the reasons for their use in image processing, their use and the problems main positive factors associated with their consideration in the lensless camera's construction. The diffraction gratings most common types examples that are currently used in the lens-free camera's construction are given, their classification and approximate structure with giving their transfer functions mathematical description is given, and their use practical examples in solving various problems associated with image processing are considered. The various diffraction gratings basic advantages and lacks consideration analysis at lensless cameras construction and their use reasons are performed. Also, the questions connected with their further development at image processing construction and use in problems are considered.

1. Introduction

In the 19th century middle, man invented photography, which allowed him to stop “the moment”. The chemical photography era began to come to an end with the digital cameras advent (1975). Nowadays digital cameras have become very widespread and are available on almost every mobile phone. But the approach to their construction has not changed - high-quality optics makes it possible to obtain high-quality images. In the 21st century, a new paradigm began to appear and to be realized: image forming based on computational methods, which allowed to speak about the alternative approaches possibility to the display systems design [1-3].

Currently, lensless imaging systems use diffraction gratings, which scatter light rather than focusing it as lenses do, to make the information useful contained in the projected image phase. The light passing the result through the lattice is a blurry image that is difficult to read, but this optical image contains enough information to make a fully legible image, using digital processing called “image restoration”. Nowadays, there are ways a lot to process the measurement results obtained by diffraction gratings means which are also called coding diffraction gratings [4].

Thus, the image phase information use (DiffuserCam or FLATCAM) is a lensless camera using different kinds' phase masks standing the sensor in front, i.e. image sensor. Such a system can be used for both 2D photography and 3D image reconstruction [4,5]. The resulting image on the sensor is light flux which is the interaction result between the image and the phase mask diffraction pattern, which significantly affects the resulting image [4]. By solving the inverse problem relative to the image obtained on the sensor taking into account the phase mask the resulting initial image transfer function can be of higher quality than without using the phase mask [6]. It should be noted that the computer
technology and optimization systems development for solving inverse problems allows obtaining higher quality images in cases a number as compared with images obtained by using conventional lens optics. Any light source is an electromagnetic oscillation that has both amplitude and phase. However, most technical devices display only the amplitude picture (i.e., the light flux intensity) and, as a consequence, there is no way to directly measure the light flux phase. Knowing the phase is extremely important as it is highly informative. This is especially important in biological imaging, where cells are usually transparent (i.e., invisible when recording only the light flux intensity) but has the light flux different phase delays. The works number in this field is very large [7-12]. Similarly, it can be noted that three-dimensional phase imaging also shows volumetric images using phase value information [13-15]. In this regard, works a number are devoted to the lens optics and phase masks combination, which in some cases can significantly improve the obtained images quality [16]. Thus, the current focus is on the various phase masks formation, including those with specified properties, i.e., their synthesis in solving specific problems. It should be noted that the imaging system focus resolution and depth are related to the system output diameter. The resolution improves with magnification, but the focus depth decreases at the same time. The imaging system focus on increasing the depth problem at the output aperture a fixed size is still relevant today. Wavefront coding technology proposed by E R Dowski and W T Cathey [17,18], solves this problem to some extent. This technology not only increases the focus depth without the optical system resolution loss but also makes it possible to reduce the aberrations' some types effect, both chromatic and off-axis. At present, wavefront coding technology is widely used in various fields [11,12,16] and makes it possible to image objects at different distances in the same contrast.

2. Diffraction gratings and their properties
Diffraction lattice is obstacles and holes a large number a set concentrated in a limited space, on which light diffraction occurs [5]. A distinction is made between irregular and regular diffraction gratings. A diffraction lattice is irregular if the holes and obstacles are distributed randomly. A regular grid has holes and obstacles distributed according to a certain law. Diffraction gratings can be superficial or spatial. They can also be divided into amplitude and phase. Amplitude - modulates the incident light amplitude by transmitting, blocking, or attenuating photons. For fabrication ease, light binary amplitude and modulation by casting shadows are usually used. Hence, an amplitude mask PSF is its shadow. An important issue when using an amplitude mask is the light bandwidth. Since the mask modulates the light by creating shadows, photons a significant number are lost, resulting in sensor capture with a low signal to noise ratio (SNR) [3, 5]. Low SNR is undesirable for low-light and photon-limited imaging scenarios such as fluorescence or bioluminescence imaging [6, 16]. In addition, decoding a lens less sensor capture tends to amplify noise resulting in poor reconstruction. Amplitude masks also suffer from diffraction effects that limit the achievable PSF range.

The phase mask modulates the incident light phase according to wave optics principles. Phase masks allow the light most to pass through, providing a high signal to noise ratio. Consequently, they can be used for low-light scenarios with a lensless camera. Lensless cameras a common feature is that they do not implement an object a direct two-point mapping to an image, as traditional cameras do. Instead, they encode the object information in sensor dimensions that require reconstruction to produce the original image. In addition, image reconstruction mainly involves solving an ill-conditioned inverse problem. The classical image reconstruction algorithm is based on the optimization principle.

“Basic” masks improvement such as 1-D diffraction gratings is possible by changing the zone profile. For example, one can consider an amplitude 1-D diffraction grating whose transmittance function changes according to the law [19],

$$\cos^2 \left(2\pi \frac{x}{d}\right),$$

where $d$ is the lattice period.

However, in practice, taking into account such gratings fabrication errors is associated with difficulties a number. One-dimensional binary amplitude and phase diffraction gratings a natural
development are corresponding two-dimensional (2-D) radially symmetric gratings (zone plates), such as the Rayleigh-Soret zone plate, which is variable thickness dark and light rings a set, as well as using a Fresnel zone aperture [20, 21]. Two-dimensional phase lattices can be obtained from one-dimensional ones by multiplying the two one-dimensional lattices phase functions, a two-dimensional binary lattice is obtained from two one-dimensional binary lattices. Such a lattice has an approximate 30% reduction in diffraction efficiency compared to a one-dimensional lattice [1].

Consider a one-dimensional unit power phase mask or a phase function in normalized coordinates, e.g. [19].

\[
P(x) = \begin{cases} 
\frac{1}{\sqrt{2}} \exp[j\theta(x)] & |x| \leq 1 \\
0 & \text{otherwise}
\end{cases}
\]

where \( j = \sqrt{-1} \), \( \theta(x) \) - is some undefined nonlinear function. This phase function knowledge determines the incoherent optical system PSF and OTF for all mismatch values.

In the cubic mask in normalized coordinates, is defined as [22, 23],

\[
P(x) = \begin{cases} 
\frac{1}{\sqrt{2}} \exp[j\alpha x^3] & |x| \leq 1, \ |\alpha| \gg 20 \\
0 & \text{otherwise}
\end{cases}
\]

where the constant \( \alpha \) controls the phase deviation.

Wavefront encoding with linear phase masks works by creating an optical transfer function that encodes distance information. Cubic phase mask wavefront encoding works to uniformly blur the image using a cubic waveform plate so that the intermediate image, the optical transfer function, is out of focus by a constant amount. Digital image processing then removes the blurring and introduces noise depending on the processor physical characteristics [24]. Dynamic range is sacrificed to increase the field depth depending on the filter used type, but optical aberration can be corrected. The mask was developed using the ambiguity function and stationary phase method [25].

An ideal diffraction mask is called a GZP and its amplitude transfer function has the form [21, 26].

\[
T(r) = \frac{1}{2} + \frac{1}{2} \cos \left( \frac{\pi r^2}{r_1^2} \right).
\]

However, such a belt plate is difficult to fabricate due to its sinusoidal change in transmission coefficient. FZA with the binary transmission is a more practical alternative mask.

However, a difficult inverse problem remains due to the reconstructed signal low ratio to noise. Current implementations require multiple masks or multiple images for noise reduction reconstruction. We propose a single lens less image with Fresnel zone aperture and incoherent illumination. By using the Fresnel zone aperture to encode incoherent rays in a wavefront-like shape. [21-27] The FZA mask transfer function:

\[
T(r) = \frac{1}{2} + \frac{1}{2} \text{sgn} \left[ \cos \left( \frac{\pi r^2}{r_1^2} \right) \right].
\]

where \( r_1 \) denotes the innermost zone radius, \( r \) is the radial distance from the aperture centre, the sign is the signum function, which is +1 for positive numbers - 1 for negative numbers.

In [26], three FZA masks with different \( r_1 \) are used to check the resolution, that is, the diffraction effect limits the resolution. Except for the double image noise, the measurement can be corrupted by other noise and arising errors mainly from three sources: sensor, mask and diffraction. Sensor noise consists of quantization noise and current noise. This noise impact on the reconstruction is relatively
small and can be reduced by improving the bit depth and increasing the exposure time. Mask error is caused by the transmission coefficient binarization. Binary FZA, as a substitute for GZP, consists of only transparent and opaque zones [24]. As the zone width decreases, the diffraction effects become more prominent. Thus, the contrast also depends on the radius. This decrease, in contrast, leads to model error and limits the reconstruction resolution. The mask can be improved by adopting a well-designed diffractive optical element to obtain the desired diffraction pattern. According to CDM-Optics, wavefront encoding can correct optical aberrations of all kinds associated with the focus, such as astigmatism, spherical aberration, field curvature or chromatic aberration. Wavefront encoding falls under the computer photography broad category as a method to increase the field depth [17, 18].

At present, the wavefront coding technique is widely used in various fields [3, 6, 11] and makes it possible to image objects at different distances in the same contrast. A phase mask placed at a classical optical imaging system changes output wavefront shape so that the system becomes a defocus-independent optical transfer function (OFT) module. Note that the phase mask presence changes the system point blur function (PRF), which now differs significantly from the $\delta$-function and in the case of cubic phase is an Airy function. This spoils the in-focus image, but the out-of-focus FRT is now the same as the in-focus one. Thus, the image is distorted in the same way over a long stretch (theoretically, the focus depth increases times several tens [24, 33]).

The image reconstruction, which is now defocusing independent, can be digitally reconstructed. System output a cubic phase apodization was originally proposed and is commonly used, but phase functions other types, logarithmic [34] and with different degree dependence, are also considered [5, 29, 35]. Currently, special attention is being paid to the phase masks construction and use with a random pattern, particularly in the Perlin noise form [29-32]. Another most promising direction in the diffraction masks development is the masks synthesis for the specifically solved problem [5].

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3. Conclusions
Based on the analysis we can conclude that the masks types change from simple to the most complex and promising are masks with a random pattern or synthesized to solve a specific problem.

The image processing performance for the different phase masks was similar to that of the best-known cubic phase mask and no significant increase in image quality was observed.

The diffraction gratings use allows image reconstruction for zoom lenses using the generalized cubic phase function, which provides higher image quality without the artefacts present for the pure cubic phase function.

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