Increasing depth of field of tilted diffractive optical element with depth map estimation in the end-to-end imaging system

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Abstract

This work considers the influence of the tilt of a diffractive lens on the shape and size of the focused area. Analytical relations describing the geometry of the focused region for various spectral channels are given. The possibility of increasing by several times the size of the zone of accurate image classification using a neural network has been demonstrated. The results of the work can be used in machine vision units for robots and unmanned aerial vehicles.

Keywords

Diffractive optics, tilted lens, depth of field, depth map, image classification, convolutional neural network

1. Introduction

Optical systems are known to be sensitive to defocusing and chromatic aberration. An increase in the depth of field of the optical system makes it possible to weaken this sensitivity and its negative consequences in blurring defocused images. However, a simple increase in the depth of field (DOF) by reducing the pupil or numerical aperture of the system leads to deterioration in resolution. One way to increase DOF without degrading resolution is to “encode” the wavefront, which is actually a phase apodization of the pupil of the lens [1-3]. As a rule, apodization is accompanied not only by positive effects (an increase in DOF and a decrease in the size of the focal spot), but also by a significant change in the structure of the point scattering function (PSF) and the growth of side lobes that worsen the image properties.

A compact camera with diffractive lens mounted on a robot or drone can be used to detect and classify objects. Increasing the size of the depth of field, especially in the longitudinal direction, will improve the response time of the device. For this purpose, we propose to use the Scheimpflug principle, which is a known geometric rule describing the orientation of the camera's focus plane when the lens is tilted relative to the sensor.

In the task of classifying images, specific requirements are imposed on the imaging system. To classifythe images we use a VGG-like convolutional neural network (CNN). The CNN architecture contains seven convolutional layers and two fully connected layers. To train the network, we use the Adam solver with a fixed learning rate of 0.0001. The loss function algorithm is categorical Cross-entropy. CNN parameters number is about 3.5 M.

2. Analytical expressions for imaging system with tilted lens

Rotation of the lens about the horizontal axis, i.e. tilting the lens leads to the rotation of the focusing plane also around the horizontal axis. We will assume that the image plane is vertical. Then the axis of rotation of the focusing plane lies in the vertical plane passing through the center of the lens. The distance between the center of the lens and the axis of rotation of the focusing plane is determined by the following relationship:

$$S = \frac{f}{sin\alpha}. \qquad (1)$$

The tilt angle β of the focusing plane is set as follows:

$$tan\beta = \frac{v}{vcos\alpha - f} sin\alpha = \frac{u}{f} sin\alpha, \qquad (2)$$

where $\alpha$is the tilt angle of the lens (Fig. 1), f is the focal length, u and v are the distances from the center of the lens to the object and image, respectively. In this case, u and v are related by a modified thin lens equation.

$$\frac{1}{vcos\alpha} + \frac{1}{ucos\alpha} = \frac{1}{f} \qquad (3)$$

The depth of field zone is converted to a wedge for a tilt lens. The apex of this wedge is at the point of rotation of the focal plane (Fig. 1). The width of this wedge can be determined at a distance u from the center of the lens. The distances w_u and w_d are equal to each other and are determined by the equation by the following relationship:

$$wx \approx \frac{Nc}{f} \frac{u}{tan\alpha}, \qquad (4)$$

where N is the lens f-number and c is the circle of confusion.

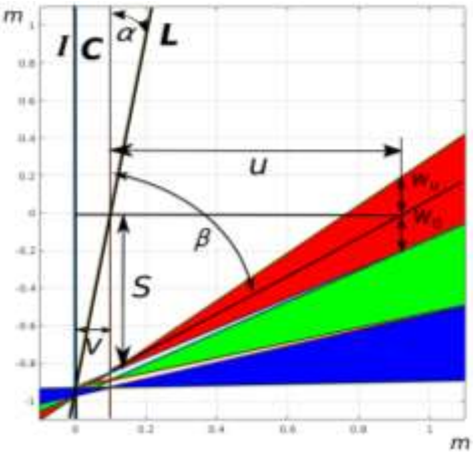

Figure 1: Tilted lens geometry. *I* stands for the vertical plane of the sensor, *C* is the vertical plane passing through the center of the lens, *L* is the plane of the lens, α is the tilt angle of the lens, β is the tilt angle of the focusing plane

3. Conclusions

A new approach is proposed to increase the depth of field of the optical system with tilted binary optical element for machine vision problems. It is shown that the tilt of the diffractive element leads to a change in the shape of the focusing region. This area takes the shape of a wedge in the longitudinal direction. This can be used to reduce the reaction time of the computer vision unit of robots and unmanned aerial vehicles.

4. References

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