Optik - International Journal for Light and Electron Optics 169 (2018) 16–26

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.com/locate/ijleo

Fast Shape-From-Focus method for 3D object reconstruction

Dalibor Martišek

Institute of Mathematics, Faculty of Mechanical Engineering, Brno University of Technology, Czech Republic

ARTICLE INFO

Keywords:
Shape-From-Focus method
Fourier transform
Phase correlation
3D reconstruction

ABSTRACT

Shape-From-Focus method (SFF method) is a method for recovering depth from an image series which are taken with different focus settings. For method presented in this paper, the series must be taken with an optical device (optical microscope, CCD or classic camera) with very small depth of focus, different images must be focussed to different planes and may be taken with inconsiderable angle of view. Proposed method is capable to registered images with different scaling, it makes possible to construct full sharpened 2D image and also the 3D model of scanned object. Accuracy of the method is tested by comparing with 3D models obtained by confocal microscope in hardware supported confocal mode.

1. Introduction

Three-dimensional reconstructions of object surfaces play an important role in many branches. As an example, morphological analysis of fracture surfaces reveals information on mechanical properties of construction materials (see [1–4]). In our paper we will deal with the 3D reconstruction using the Shape-From-Focus method (SFF method). This is a method for recovering depth from an image series which are taken with different focus settings – so caled multifocal image. For an image to be sharp, the object must be placed exactly in the plane to which the microscope or camera is focused (so caled a sharpness plane). However, in many cases, we cannot take the observed object to be a plane, and therefore this condition cannot be fulfilled. The points which are placed in the sharpness plane and its nearby surrounding will be displayed as sharp. These points create so caled optical cut (or optical section), the others are displayed as blur. To create a sharp 2*D* image, it is necessary to obtain a series of images of the same object, each of them with different focussing, optical cuts must cover whole image. 2*D* reconstruction involves the composition of the optical cuts to a new image. There is also a simple method for constructing a rough 3*D* model, where all points belonging to the same optical cut have the same height – we obtain a staircase approximation. This is a principle of a confocal microscope. Optical cuts are recognized by hardware (using laser beam), following staircase approximation may be very precisely because the microscope is able to recognize up several hundreds levels.

Standard optical devices (optical microscopes, CCD or classic cameras) are able to acquire several tens of optical cuts. The main problem is, how recognize the optical cut between blured parts on the analysed image. Tenebaum [5] developed the gradient magnitude maximization method that uses the sharpness of edges to optimize focus quality. Jarvis [6] proposed the sum-modulus-difference that is computed by summing the first intensity differences between neighboring pixels along a scan-line and is used as a measure of focus quality. Schlag et al. [7] implemented and tested various automatically focusing algorithms. More recently, Krotkov [8,9] evaluated and compared the performance of different focus criterion functions. Krotkov also proposed a method to estimate the depth of an image area. Pentland [10] suggested the evaluation of image blur to determine the depth of image points. Grossmann [11] has proposed the estimation of depth of edge points by analyzing the blur of the edges due to defocusing. Darrell and Wohn [12] have developed a depth from focus method that obtains an image sequence by varying the focus level and uses Laplacian and Gaussian pyramids to calculate depth. Subbarao [13] suggests the change of intrinsic camera parameters to recover the depth map of a scene. Ohta et al. [14] and Kaneda et al. [15] have used images corresponding to different focus levels to obtain a single level of high focus quality.

https://doi.org/10.1016/j.ijleo.2018.05.014
Received 19 October 2017; Accepted 2 May 2018

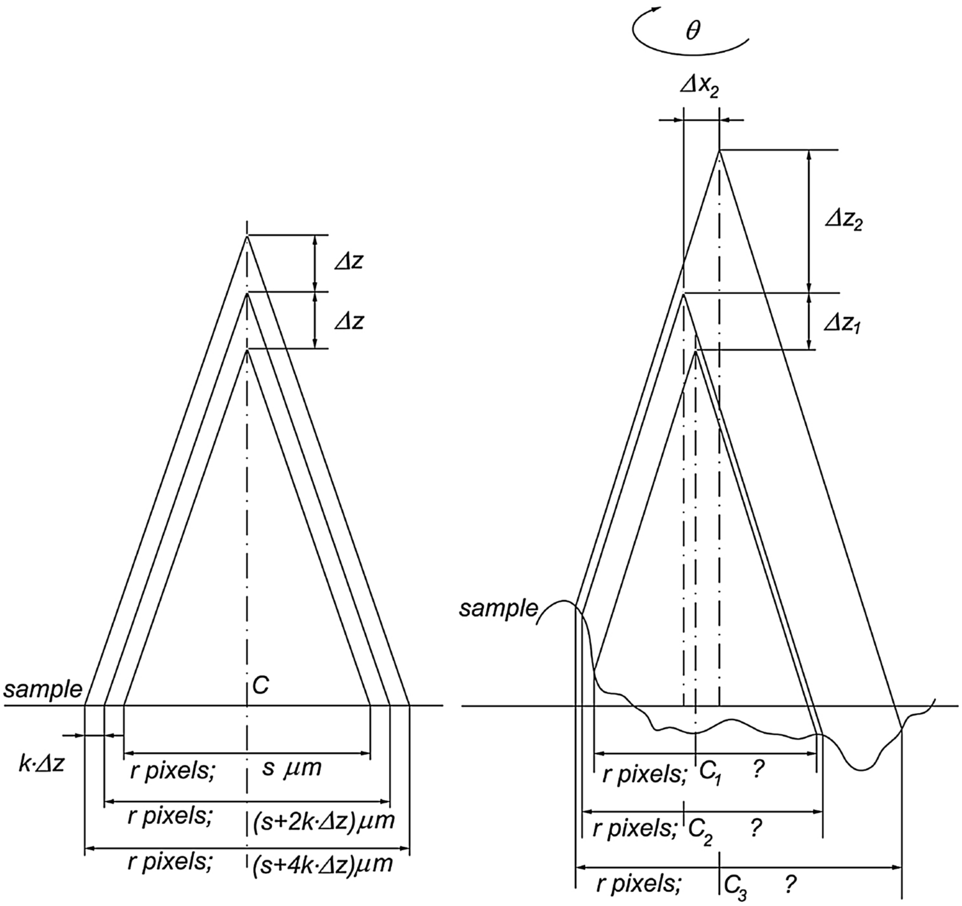

Fig. 1. The central projection of large sample – ideal case on the left is solvable using elementary mathematics, real case on the right requires sophisticated mathematical tools.

Some publications recomend to use sharpness detectors based on Fourier transform – Martišek [16], Ficker [17], Martišek et al. [18]. One of the last publications in this branch (Ficker [19]) uses software based on Fast Fourier Transform (FFT). We can read: *„The software realizing the 3D reconstructions within the SFF method was completely written in our laboratory.“* This statement is at least very inaccurate. This software – Shape-From-Focus Modeller (SFFM) – has been continuously developed since 2000 by the author of this article, independently of any laboratory. First results author published in [16]. Various authors used it for achievement and publication their results – see [17–22] for example. Unfortunately, in some publications, outdated versions of this software was used, moreover, no reconstruction was made in an optimal way [19,22,23,25,26].

2. Non-confocal reconstruction

2.1. Preprocessing

SFFM assumed that the field of view is small and the used projection is parallel until version 2011. The paper [16] and many other works ([17,18,20,21–23,25,26] for example) presume this projection. In parallel projection, all images are provided in field of view with the same size. However, this assumption is not valid in case of a standard camera and larger samples – projection lines angle is not negligible and view fields of individual images are different.

Various image scale was solved using elementary mathematics only until 2015. We presumed the image size is proportional to the camera shifting (see Fig. 1 on the left). However, the practical situation is more complicated. The images differ not only in used scale but also in displayed content (different parts are focussed in different images). Due to mechanical inaccuracies, the step in the z axis may be not fully constant, the images can also be mutually shifted in x - or y -axis and even rotated. Image registration is also complicated by non-planarity of samples (see Fig. 1 on the right). Therefore, sophisticated preprocessing of the image series is necessary. A suitable tool for this preprocessing is the Fourier transform and phase correlation.

The standard definition of the Fourier transform of a function of two variables is as follows [27].

Let $f(x; y): \mathbb{R}^2 \to \mathbb{C}$ be a function such that $\iint_{\mathbb{R}^2} |f(x; y)|\, \mathrm{d}x\mathrm{d}y$ exists and is finite. The *Fourier transform* of f is