Optik 126 (2015) 2050–2054

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Enhancement of fish-eye imaging quality based on compressive sensing

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ARTICLE INFO

Article history:
Received 7 April 2014
Accepted 18 May 2015

Keywords:
Compressive sensing
Reconstruction
Fish-eye
Spatial resolution

ABSTRACT

Compressive sensing is a novel theory in signal acquisition and reconstruction, which states that the original signal can be reconstructed with few data. Limited by the computer memory, the image must be partitioned into small regional blocks for the reconstruction, especially when dealing with fish-eye images. However, the reconstruction has a major shortcoming, that is, the image block is more blurred at the edge of the reconstructed image than at the center. This phenomenon is caused by the adoption of similar sampling rate to different image blocks in the traditional process. Given that each image block has different spatial resolutions, the sampling process is not reasonable. This paper proposes the fish-eye camera spatial resolution first. Afterward, the sampling rate of different image blocks is improved according to spatial resolution. Finally, some numerical experiments are performed. Results of the numerical experiments show that the method proposed in this study is effective.

1. Introduction

The use of omnidirectional cameras has widely increased in recent years. The major advantage of omnidirectional cameras is that they can provide a wide field of view, which provides users with a perspective of the whole scene. These cameras have been used in different areas, such as surveillance [1], active vision [2], and robotic football. According to the single-view point, this type of camera can be classified into two: central and non-central. Among the non-central cameras, an important type of camera is named fish-eye. This camera is composed of fish-eye lens and conventional camera. Given that the fish-eye lens can be easily mounted on standard CCD or CMOS conventional camera [3], they have been popularly used in many places.

However, using the fish-eye camera has disadvantages. First, the image taken from a fish-eye camera is distorted. Second, the area of object in the image is smaller than that in the conventional camera when the two cameras are used at a similar location. This limitation is the major disadvantage of the fish-eye camera. Increasing the area of CCD or CMOS to solve this problem can be considered as an effective method. Unfortunately, unlimitedly increasing the area of CCD or CMOS cannot be performed because of the limit of hardware level. Third, the image block is not clear/sharp at the edge of the fish-eye image. The theory of compressive sensing offers another way to solve the last two problems.

The novel theory of compressive sensing, which is also named compressed sensing or compressive sampling or sparse recovery [4], states that reconstructing signals or images can be performed from few measured data. The super-resolution under the signals or images can be approximated by a sparse expansion in terms of suitable basis. Suppose $x \in R^N$ is a K-sparse signal in basis ψ so that $x = \psi x_0$, with $\left|\mathrm{supp}(x_0)\right| \le K \ll N$, where $\mathrm{supp}(x) = \left\{ j : x_j \neq 0 \right\}$. When x is compressible in basis ψ, it can be approximated by some algorithms. Consider a random measurement matrix Φ with size $M \times N$ and the two parameters satisfy $M < N$, which make up vector y, and are made such that $y = \Phi x = \Phi \psi x_0 = \Theta x_0$. x can be reconstructed through its sparse coefficient x_0 by solving the following minimization-constrained optimization problem:

$$\widehat{x_0} = \underset{x_0}{\operatorname{argmin}} \|x_0\|_0 \quad \text{s.t.} \quad y = \Phi \psi x_0 \tag{1}$$

Unfortunately, Problem (1) is NP hard. Solving Problem (1) is extremely time consuming. However, Candès and Tao [5] proved that under a stronger condition, the sparse reconstruct problem is equivalent to a convex program. In other words, when Θ satisfies some stronger condition, which is named restricted isometry property, which is also named restricted isometry condition

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http://dx.doi.org/10.1016/j.ijleo.2015.05.077

(RIC), Problem (1) can be solved by determining the following minimization-constrained optimization problem:

$$\widehat{x_0} = \underset{x_0}{\arg\min} \|x_0\|_1 \quad \text{s.t.} \quad y = \Phi\psi x_0 \tag{2}$$

Many algorithms, such as Orthogonal Matching Pursuit (OMP) [6], Subspace Pursuit (SP) [7], Total Variation (TV) [8], and Gradient Projection for Sparse Reconstruction (GPSR) [9], can be used to solve Problem (2). Limited by the computer memory, the image must be partitioned into some small blocks with size 32 × 32 or 64 × 64 for reconstructing the original image. In the high-resolution image, too many image blocks exist if this method is used. For example, 768 image blocks exist with size 64 × 64 for a 1536 × 2048 fish-eye image. When reconstructing the image, the value of parameter M, which is also named number of measurements as a constant for different image blocks, is set. Given that the different image blocks for an actual image have different resolutions, the process is not reasonable. Thus, if the resolution of the camera is considered in setting the number of measurements, the process should be more reasonable.

Too many definitions of camera resolution exist, such as CCD or CMOS, angular [10], and spatial resolutions [1]. The CCD or CMOS resolution only means the size of CCD or CMOS and the angular resolution have strong direction. Using these definitions to set the number of measurements of the fish-eye image is not reasonable. Thus, considering the definition of spatial resolution in setting the value of the number of measurements will be a good choice. Unfortunately, no literature discusses the fish-eye camera spatial resolution. Calculating the spatial resolution of the fish-eye must be determined first.

This paper is organized as follows: Section 2 proposes the fish-eye camera spatial resolution. The fish-eye camera spatial resolution formula, which has not been studied in other papers, is obtained based on the definition of spatial resolution of conventional camera proposed by Nayar in 1999 [1] and equidistant projection model of the fish-eye camera. Section 3 succinctly introduces the theory of compressive sensing. Then, based on the spatial resolution of the fish-eye camera, the method on how to change the number of measurements of different image blocks is introduced. Section 4 discusses the experiments conducted to check the proposed method. Some of the experimental results are also shown. Section 5 presents the conclusions of this study.

2. Spatial resolution of a fish-eye sensor

Analyzing the spatial resolution of a fish-eye requires an understanding of the fish-eye camera imaging. Fig. 1 shows the fish-eye camera system, where point O is the center of convergence of incident light rays and z axis is the optical axis. The angle between optical axis and incident ray is θ. The distance between incident ray that arrives at an image point and optical axis is r. The fish-eye lens designers design the lens to follow one of the following projections [11–13]:

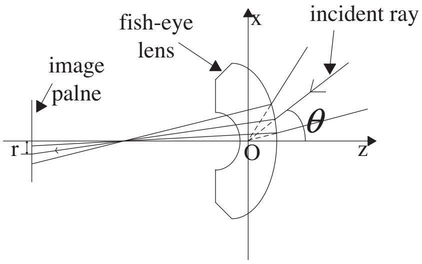

Fig. 1. Geometrical optics model of a fish-eye lens system.

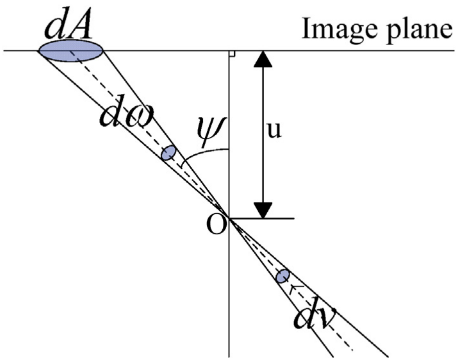

Fig. 2. Geometry used to derive the spatial resolution of conventional camera.

$$\begin{cases} r = f\theta & \text{(equidistance projection)} \\ r = 2f\tan\left(\theta/2\right) & \text{(steregraphic projection)} \\ r = 2f\sin\left(\theta/2\right) & \text{(equisolid angle projection)} \\ r = f\sin\left(\theta\right) & \text{(orthogonal projection)} \end{cases} \tag{3}$$

Discussing the spatial resolution of other types of cameras besides the conventional one is very difficult. Only few studies discuss spatial resolution. Fortunately, Nayar and his partners provided the definition of spatial resolution and discussed the spatial resolution of different types of catadioptric cameras in detail. However, he did not analyze the spatial resolution of the fish-eye camera, and no other studies discuss it. Thus, the definition of the spatial resolution must be followed to discuss the topic. Fig. 2 shows the infinitesimal area dA on the image plane. If this infinitesimal pixel image is an infinitesimal solid angle dv of the world, the spatial resolution of the camera as a function of the point on the image plane at the center of the infinitesimal area dA is as follows [1]:

$$\frac{\mathrm{d}A}{\mathrm{d}v}. \tag{4}$$

If ψ is the angle made between the optical axis and the incident ray joining the pinhole to the center of the infinitesimal area dA (see Fig. 2), the solid angle can be calculated by the infinitesimal area dA at the pinhole [1]:

$$\mathrm{d}\omega = \frac{\mathrm{d}A \times \cos\psi}{u^2/\cos^2\psi} = \frac{\mathrm{d}A \times \cos^3\psi}{u^2} \tag{5}$$

Therefore, the spatial resolution of the conventional camera is as follows:

$$\frac{\mathrm{d}A}{\mathrm{d}v} = \frac{\mathrm{d}A}{\mathrm{d}\omega} = \frac{u^2}{\cos^3\psi} \tag{6}$$

Nevertheless, the fish-eye camera only follows Formula (3), which means it does not follow the pinhole model. Thus, Formula (6) does not satisfy the fish-eye camera. Determining its spatial resolution must start with the original definition of the conventional camera. Fig. 3 shows that dA is the infinitesimal area on the image plane and ψ is the angle between the optical axis and the line joining point O to the center of the infinitesimal area dA. Angles θ_1 and θ_2 are the incident angles between the incident ray and the optical axis. The solid angle dv is the solid angle of the world of the infinitesimal area dA. Setting the length of CD as dl, AB as dl', and AE is l, the spatial resolution of the fish-eye camera can be determined if the fish-eye camera follows the equidistant projection.