Seamless Focal-Stack Refocusing

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***Abstract*—A camera with the refocus function offers users the convenience of changing the focal plane of an image after it is shot; no photo reshooting is necessary. Unlike the light field solution, focal-stack refocusing is a cost-effective solution that takes a sequence of photos (the so-called focal stack) of a scene by sweeping the lens and creates the refocus effect by selecting from the focal stack the sharpest photo for the object specified by the user. However, switching from one focal plane to another as the user navigates through different objects creates radial image expansion or contraction as a result of corresponding lens movement. A slight distortion of this kind can be quite annoying to the user. In this paper, we develop an effective method to remove the annoying distortion. A seamless refocusing is achieved.**

I. Introduction

Focusing is a process to determine in-focus lens position so that the sharpest image can be captured. Conventional cameras require the focus window to be placed on the object of interest when taking a photo so that a sharp image of the object can be generated. Once a photo is taken, the user cannot bring a different object to focus. In contrary, a camera with post-capture refocusing capability allows the user to change the in-focus object after the photo is captured. Therefore, it is desirable to equip conventional cameras with the post-capture refocusing capability.

The focal-stack refocusing approach involves two basic operations. The first operation takes a stack of photos at different focal planes by sweeping the lens across its dynamic range. The second operation chooses from the focal stack the sharpest photo for the object specified by the user. At the cost of additional memory for storing the focal stack, this approach can produce the refocus effect of light field cameras.

Each photo in the focal stack is captured with the lens at a different position. As the lens moves, the focal plane changes. An object located on the focal plane would have sharp image, whereas an object outside the focal plane would suffer a certain degree of blur, depending on its distance to the focal plane. Furthermore, as the lens moves, its distance to the image sensor changes, introducing radial expansion or contraction to the image. Although small, such radial image distortions result in unpleasant viewing experience when the user navigates through a series of objects in the image. The goal of this paper is to eliminate such annoying effect for focal-stack refocusing.

II. Algorithm Description

Let F_1, F_2, …, and F_n be the n images of a focal stack, each of resolution $M \times N$. Let *refocus*$(\cdot,\cdot)$ be a function that takes an pixel at (x,y) as input and returns an index $i \in 1, 2, \ldots, n$ that points to F_i as the sharpest image at p. In other words, p is best focused in F_i. The focal stack is stored in an $M \times N \times n$ array S,

$$S = \{F_i \mid i \in 1, 2, \ldots, n\} \tag{1}$$

We convolve each photo F_i with the energy of Laplacian (EOL) kernel to calculate its gradient G_i,

$$G_i = F_i \otimes K \tag{2}$$

Where $\otimes$ denotes the convolution operation and K denotes the EOL kernel. The resulting image gradient of the focal stack is stored in an $M \times N \times n$ array G.

We sum up G_i values in a $(2d_x+1)\times(2d_y+1)$ window centered at p as a measurement of the sharpness of F_i at p. The result is stored in an $M \times N \times n$ array R.

In our implementation, we choose d_x and d_y, respectively, as one tenth of the width and height of the photo, truncated to integer. While the image gradient array G indicates how a pixel is different from its neighbors, the array R provides information about the sharpness of a pixel in the focal stack.

Finally, an $M \times N$ index map is used to store the results of the function *refocus*$(\cdot,\cdot)$ for all possible inputs. Each entry of the index map tells which photo in the focal stack is the sharpest for the pixel corresponding to the location of entry.

We use the thin lens model to formulate our model. In Fig. 1, p_0 is the lens to object distance and q_0 is the lens to real image distance, i.e., the distance from lens to image sensor. f is the focal length. H_0 and h_0 are the object size and image size, respectively.

Since the lens movement of a camera is small with respect to the distance of the object to the camera (lens), we may assume that object distance is a constant and that the lens movement only change the image distance and the image size of the object. Consider, for example, q_1 and q_2 in Fig. 2 that represent the image distances corresponding to lens movements d_1 and d_2. Let h_1 and h_2 denote the corresponding image sizes. In this simplified model, the image size is proportional to its image distance. The ratio is fixed. In other words, we formulate our model as a linear model.

A test is performed to verify the linear model, which is used to scale the photos in a focal stack. Figs. 3a and 3b show two photos in a focal stack, and Fig. 4 shows the estimated radial expansion of the feature points (the crosspoints of the checkboard pattern in Figs. 3a and 3b). In Fig. 4, each group of corresponding feature points in a focal stack form a line with correlation coefficient higher than 0.93. This strongly suggests the validity of the linear model used in our approach.

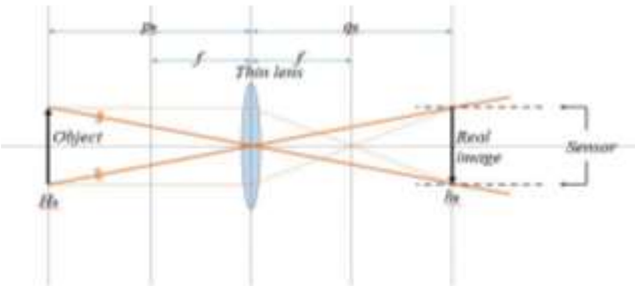


Fig. 1. Simple model for imaging.

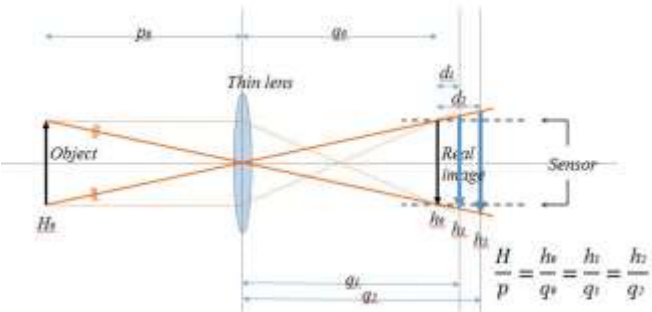


Fig. 2. The optical path for moving lens.

(a) The 5th image in a focal stack (b) The 15th image in a focal stack

Fig. 3. Images in a focal stack.

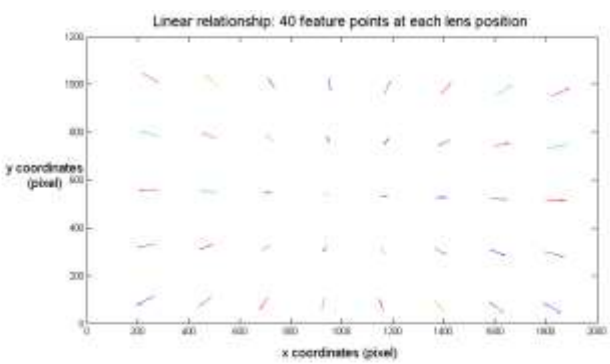
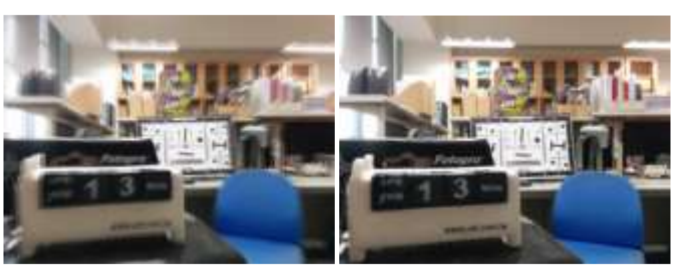


Fig. 4. Radial image expansion.



(a) Before rectification (b) After rectification

Fig. 5. The 22nd image and the 46th image in a focal stack are overlapped to show the result. (a) Overlapping image before rectification. (b) Overlapping image after rectification.

Our algorithm consists of two steps. In the first step, it expands the images in a focal stack and uses the image captured by the camera at the maximum lens distance as the reference image to compute the radial expansion for other images in the focal stack. In the second step, it crops the pixels outside the image frame for each expanded image.

Specifically, we use three parameters (the scaling ratio r_i and the displacement (Δ_x,Δ_y) of image center) to model the expansion and solve these parameters by using an optimization method. Suppose F_i is to be expanded to $F_i{}'$ so that it matches F_j. The problem is formulated as follows:

$$\min_{r_i,\Delta_x,\Delta_y} \left\| F_i' - F_j \right\|_2 \tag{3}$$

We use the optimization solver fmincon of Matlab to find the optimal parameters.

III. Experimental Result

We implement our methods on an Android Nexus 5. Fig. 5a is generated by overlapping two images from a focal stack. The annoying radial distortion can be easily observed, whereas in Fig. 5b, the two rectified images are perfectly matched. The result of our focal-stack refocusing algorithm is made available online and can be viewed at *https://youtu.be/CJ_ZTGEt-cg*. In the video, once the cursor is pointed to an object of interest, the sharpest image of the object appears without the annoying image expansion or contraction effect.

IV. Conclusion

Focal-stack refocusing is a very useful function for digital cameras since it generates high quality refocused image similar to the one generated by a light field camera but at a much lower cost. In this paper, we have developed an effective algorithm to remove the annoying radial expansion/contraction distortion of focal-stack refocusing. This is achieved by employing a linear model to account for the radial expansion and an optimization solver to find the optimal model parameters. It should be noted that the optimization is performed offline and the resulting parameters are applied on the fly during refocusing. A much more pleasant viewing experience is achieved.

Reference

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