Improving Shape-from-Focus by Compensating for Image Magnification Shift*

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Abstract

Images taken with different focus settings are used in shape-from-focus to reconstruct the depth map of a scene. A problem when acquiring images with different focus settings is the shift of image features due to changes in magnification. This paper shows that those changes affect the shape-from-focus performance and that the final reconstruction can be improved by compensating for that shift. The proposed scheme takes into account the effects due to magnification changes between near and far focused images and it is able to determine the depth of the scene points with higher accuracy than traditional techniques. Experimental results of the application of the proposed method are shown.

1. Introduction

Shape-from-focus (SFF) is a passive method for recovering 3D shapes by estimating the distance to every point of a scene according to its degree of focus in separate images taken with different focus settings. As will be described later, the frame number at which a point is best focused is directly related to its depth.

When focusing on a scene, every image point shifts and changes its magnification. However, this effect is rarely considered in practice, since for short focusing ranges, the shift and magnification changes can be neglected. This limits the application of SFF to short distance ranges. Therefore, in order to apply SFF to larger distances and to improve its performance at short distances, the image shift problem must be addressed. This paper presents a method for improving the application of focus measure operators in SFF in the presence of image shifts. Instead of applying those operators at fixed positions as in previous works, the position of the operators is changed based on image feature shifts estimated through phase correlation. Experimental results show that the proposed technique determines the depth of the points in a scene more accurately than previous methods.

This paper is organized as follows. The next section describes previous related work that addresses the image shift problem in SFF. Section 3 describes the new approach for improving SFF in the presence of changes in image magnification and feature shifts. Experimental results are shown in section 4. Finally, conclusions are given in section 5.

2. Background

In fig.1(a), when a point P is located at a distance u from the lens, it will be focused with a magnification $m = H_i/H_o$ when the sensing device is located at a distance v from the lens. The change of focus in a camera is often modeled as a translation of the sensing device. Thus, when focusing to different distances, $u_1$ and $u_2$, the sensing device will move from $v_1$ to $v_2$, causing P to change its magnification $^1$, as shown in fig.1(b). Based on the thin lens equation, the change in image magnification caused when moving the “in-focus” position from $u_1$ to $u_2$ can be estimated as:

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1Although the defocusing of P causes its radiance to spread along a blurring circle, the effective location of P can be considered to be the center of this circle, which lies along the principal ray that passes through the center of the lens [6]
\[ \chi_m = \frac{u_2(u_1 - f)}{u_1(u_2 - f)} , \]  
where \( \chi_m \) is the ratio between image magnifications \( m_2 \) and \( m_1 \). In (1), note that \( \chi_m \) only depends on \( u_1 \) and \( u_2 \). Therefore, when focusing the camera from \( u_1 \) to \( u_2 \), the magnification of any scene point will change by a factor of \( \chi_m \) independently of the position of the real point itself.

The side effect of focusing in magnification has been noticed by many researchers and some attempts have been made to address the feature shift problem in SFF. The use of larger evaluation windows for the focus measure operator at the cost of spatial resolution was considered in [3]. In [1], a distortion map is computed by taking images of a test pattern and tracking some key points. The information of the distortion map is then used to predict pixel shift due to changes in focus. The drawback of this method is that it depends on the accuracy to track the key points of the pattern and also requires calibration data stored as a function of camera parameters. In [6] and [7], the effect of focusing in magnification is compensated for by means of optics. Watanabe and Nayar [6] proposed the use of a telecentric lens system in which magnification is kept constant relative to focus variations. Willson [7] proposed the use of zoom to compensate for magnification changes due to focusing. In this approach, a zoom value must be determined to compensate for the changes in image magnification for every change in focus position. Both in [6] and [7], either complex controllable optics or lens calibration procedures are required. The method proposed in this work to deal with feature shifts due to changes in magnification only uses the information present in the image frames, with no special restrictions on lens quality or calibration procedures.

3. Improved Focus Measure

3.1. Focus measure operator

When a set of images are captured from a given scene with different camera settings (usually by changing focus), some focus measure operator is used to compute the degree of focus of every pixel in each image. Since it is difficult to find an operator that accurately measures the degree of focus using a single pixel \((i, j)\), the focus is computed in a local window \(\Omega(i, j)\) around that pixel.

Let \(FM_k(i, j)\) be the focus measure computed for image \(k\) at pixel \((i, j)\). A focus measure vector \(FM\) is then defined for every pixel \((i, j)\) with as many dimensions as captured images, \(FM(i, j) = (FM_1(i, j), FM_2(i, j), \ldots FM_k(i, j))\).

The focus measure vector is used to determine the frame position at which the pixel is best focused. The reconstruction technique used to obtain the depth map from the information retrieved from the focus measures is presented in [4]. Basically, the depth associated with pixel \((i, j)\) is the in-focus distance corresponding to the image \(k\) such that \(FM_k(i, j)\) is maximum.

The local window used for computing \(FM_k(i, j)\) is valid under the assumption of a continuous shape and should be kept as small as possible. For the results shown here, a window of \(11 \times 11\) pixels was used.

Many algorithms and operators have been proposed to measure the degree of focus of an image pixel. The most popular ones are the Modified Laplacian [4], the Tenengrad Algorithm and the Graylevel Variance [2]. The results in this paper have been obtained with the Modified Laplacian defined as [4]:

\[ FM_k(i, j) = \sum_{(x,y)\in\Omega(i,j)} ML(x, y) \]  
(2)

\(ML(x, y)\) is the modified Laplacian computed as:

\[ ML(x, y) = |2I(x, y) - I(x - \Delta x, y) - I(x + \Delta x, y)| + |2I(x, y) - I(x, y - \Delta y) - I(x, y + \Delta y)| \]

As suggested in [4], only the terms in (2) which are above a threshold are summed.

3.2. Estimation of image shifts

As discussed in section 2, changes in magnification are expected when focusing. If the position and size of the neighborhood \(\Omega(i, j)\) in which the
focus measure is computed are kept constant, image feature shifts can cause the FM operator to fail measuring the degree of focus accurately. In this paper, we propose to apply the FM operator in neighborhoods that adaptively change their location as a function of image shift.

Many techniques including point matching, image correlation and FFT have been used for estimating image shifts. In this work, we use phase correlation due to its simplicity and robustness to noise. A more detailed description of shift estimation using phase correlation can be found in [5]. Preliminary tests were also carried out to compare the performance with different point tracking algorithms, such as the Black-Anandan, Lucas-Kanade and Horn-Schunck methods, and the best results were obtained with phase correlation.

Taking into account the image feature shifts due to magnification effects, the focus measure operator is applied as follows:

1. Let $I_k$ and $I_{k+1}$ be two consecutive images in a given image set. The horizontal and vertical shifts ($\Delta X_k, \Delta Y_k$) for every pixel $(i_k, j_k)$ between $I_k$ and $I_{k+1}$ are computed using phase correlation in a $M \times N$ window centered at that pixel. A Hamming window is used in this step to reduce the effects of sub-image edges.

2. The proposed focus measure vector corresponding to every pixel is defined as, $FM(i,j) = (FM_1(i_1, j_1), ..., FM_k(i_k, j_k))$, such that:

$$
\begin{align*}
(i_1, j_1) &= (i, j) \\
(i_{k+1}, j_{k+1}) &= (i_k + \Delta X_k, j_k + \Delta Y_k)
\end{align*}
$$

4. Experimental Results

A set of experiments has been carried out in order to assess the effect of image magnification and image feature shift on SFF. A set of 40 images of a textured planar surface were captured using a 3.3 mm lens motorized camera. As shown in section 2, a large focal length is expected to increase the image magnification problem. Hence, experiments performed with a small focal length will provide more general results.

Images were captured by focusing within a distance range of 68 mm. For this set of images, the flow line of every pixel was estimated using the phase correlation method as described in section 3.2. The flow lines for every pixel were computed using non-consecutive images, since for the small changes in magnification present between consecutive images, the pixel shift in most image points was lower than one pixel. In this work, one out of every five images were processed. The flow line between these images is then calculated using linear interpolation. Phase correlation can also be used to calculate image shift with sub-pixel accuracy. Notwithstanding, since digital images use integer indexing, the estimation of the compensated focus measure vector would require a different methodology and is left for future work.

In these experiments, the computed flow field had maximum shifts of 9 and 8 pixels in the X and Y directions respectively. Since the focus measure operator is usually computed in neighborhoods smaller than $15 \times 15$ pixels, those shifts are significant and will likely affect the SFF performance. For example, fig.2(a) shows the estimated feature shift for a pixel at a starting position $(i, j) = (24, 23)$, with the imaged point being 40 mm away from the camera. The pixel’s flow is computed through phase correlation using a $31 \times 31$ window centered at it. The marks in fig.2(a) indicate the images where shifts were computed. The continuous line shows the calculated pixel trajectory for the rest of images. Similar results are obtained for other pixels, although smaller shifts correspond to pixels closer to the image center. Notice that the focus measure vector obtained after compensating for image shift has its maximum at a position closer to the actual depth than the corresponding maximum without compensation, fig. 2(b).

By repeating the process illustrated in fig.2 for every pixel, the complete flow field is obtained. A depth map with compensated image shift is computed based on that field. Fig. 3(a) and fig. 3(b) illustrate the tracking capabilities of phase correlation for a certain point in the scene. Fig.4(a) and fig.4(b) compare the reconstructed depth map obtained with traditional SFF and with the proposed shift-compensated SFF to different scenes. The proposed approach clearly improves the accuracy in the location of image point depths. In particular, the RMSE of the reconstructed depth map shows improvements of up to 21%. Tests carried out over synthetic data showed improvements of up to 33% but, for space limitations, only the results on real data are shown. As expected, the most noticeable effects of image shift compensation can be observed around the borders of the scene. In order to compute the RMSE of every depth map, a surface with planar patches at the correct location was used as ground truth.
Another important issue related to the performance of the proposed technique is the fact that the flow lines of pixels near image edges can lead to out-of-limit image coordinates. Thus, to apply SFF with shift compensation, the image size must be reduced around its borders. Nevertheless, this reduction and the corresponding loss of data is necessary even if no shift compensation is applied, since, due to changes in magnification, some scene points will move out (or in) the captured image. Moreover, during point tracking, non-integer coordinates may appear. Depth-maps are thus treated as surfaces whose height is a function of continuous X-Y coordinates instead of discrete ones.

5. Conclusion

A new technique to improve the accuracy of shape-from-focus by compensating for image feature shifts due to changes in image magnification has been proposed. Unlike previous proposals for image shift compensation, this method corrects image shift based on the information present in the images of the focusing set, thus being independent of camera calibration or complex optics systems.

References