Extended depth of field for visual measurement systems with depth-invariant magnification

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ABSTRACT

Conventional optical imaging systems are limited by a fundamental trade-off between the depth of field (DOF) and signal-to-noise ratio. Apart from a large DOF, a constant magnification within a certain depth range is particularly essential for visual measurement systems. In this paper, we present a novel visual measurement system with extended DOF and depth-invariant magnification. A varifocal liquid lens is employed to sweep its focus within a single exposure of the detector, after which a blurred image is captured. The blurred image is subsequently reconstructed to form a sharp extended DOF image by filtering with a single blur kernel. The experimental results demonstrate that our method can extend the DOF of a conventional visual measurement system by over 10 times, while the change in the magnification within the extended DOF remains less than 1%.

Keywords: Visual measurement, extended depth of field, depth-invariant magnification, varifocal liquid lens

1. INTRODUCTION

Visual measurement is widely used in industrial applications such as surface defect detection, deformation detection, size measurement, and reverse engineering. Apart from lateral resolution, a large depth of field is particularly required for accurate visual measurement. While the depth of field can be enlarged by decreasing the aperture of the objective, there is a fundamental trade-off between the depth of field (DOF) and signal-to-noise ratio (SNR).\textsuperscript{1} Although the depth of field can also be extended by sophisticated optical design, it leads to very expensive commercial lens.

In the past decades, numerous computational approaches have been proposed towards achieving an extended depth of field (EDOF). Early approaches\textsuperscript{2-4} involved the application of optical sectioning and the capture of multiple images at different depth locations. Subsequently, an EDOF image was reconstructed by fusing the image stack into a single image. Since these techniques require multiple detector exposures, their application to dynamic scenes is considerably limited. Another widely studied approach is wavefront coding,\textsuperscript{5-9} wherein a phase mask is placed at the aperture of the lens. The DOF extension requires sensor exposure only once. The phase mask causes insensitive defocus of objects within a certain depth range. Subsequently, by filtering the captured image using a single blur kernel, an EDOF image is recovered. While for wavefront coding, the EDOF is determined by the particular phase mask and is therefore fixed, the EDOF in our system can be adjusted by flexibly controlling the variable focus lens. In our work, extended DOF is achieved by sweeping the focus of objective in a single exposure.

Recently, researchers have proposed the extension of the DOF by using focal sweep. A movable detector is used to scan the focus during image integration to achieve an adjustable DOF.\textsuperscript{10} The EDOF image is reconstructed by deconvolving the captured blurred image with a single integrated point spread function (IPSF). Another focal sweep method has been proposed by Liu\textsuperscript{11} in the field of microscopy, in which a liquid lens\textsuperscript{12,13} is applied to

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\end{itemize}
change the focal distance of the microscope. In our work, we also propose the use of a liquid lens\textsuperscript{11} to enable focal sweep in order to achieve EDOF. However, we apply the variable focus lens for visual measurement systems instead of microscopy systems. We assume that this focal sweep method can also contribute to telecentric visual measurement systems, which is verified by both computer simulation and experiments. It is to be noted that although the two approaches address different imaging geometries, they function with the same underlying assumption that the imaging system’s impulse response function (i.e., point spread function or PSF) is the integration of numerous PSFs corresponding to the sweep of the focal distance, and further, that the response is insensitive to different depths.

It is also noteworthy that previous approaches do not take into consideration the change in magnification over different depths. However, in the case of visual measurement systems, it is required to maintain a constant magnification within the DOF. Since visual measurement systems are required to measure sizes at different depths, a changing magnification over different depths may lead to complications in standardization along with potential measurement deviations. Differing from the previous approaches used for achieving EDOF, our method achieves invariant magnification within the extended DOF. A bi-telecentric lens is adopted to provide a constant magnification within its DOF, while the liquid lens extends the original DOF. In addition, given that the liquid lens is capable of both continuous-sweeping and discrete focal lengths, the proposed system can be easily switched between a conventional visual measurement system and an EDOF system without the requirement of hardware modifications. Therefore, our proposed system is more flexible than conventional ones.

The rest of the paper is organized as follows. In section 2, we describe average-blurred image capturing by the proposed EDOF system and establish the depth-invariance of the impulse response functions of the system by simulating integrated PSFs based on image formation theory. Section 3 presents the prototype EDOF system and the design of the varifocal telecentric objective, and the experimental results are presented in section 4. Finally, section 5 concludes the paper.

2. VOLUMETRIC OPTICAL SAMPLING AND DEPTH-INVARIANT PSFS

A schematic illustration of volumetric optical sampling for the EDOF visual measurement system is shown in Fig.1. During a single exposure of the detector, the liquid lens synchronously scans its focal distance in order for the focal plane of the imaging system to accordingly sweep through a certain depth range. The image formation on the sensor is accordingly an integration of numerous sharp images at each depth. Consequently, the captured image is blurred and requires post-processing to produce an EDOF image. It is noteworthy that due to the sweep of the focal plane, perfectly focused images at each depth are all included in the sensor integration. This implies that high frequencies of all scene depths are captured during a single exposure.

Post-processing of the captured blurred image requires the system’s response function, i.e., PSF, to be determined. Given the image formation process, the PSF of the system is also an integration of PSFs at each depth. The integrated PSF can thus be determined as
Figure 2. Simulated normal telecentric system PSFs and EDOF telecentric system IPSFs at different depths. While the PSFs in (a) vary significantly, the IPSFs in (b) are nearly invariant.

\[
IPSF = \int_0^T PSF(t) dt, \tag{1}
\]

where \( T \) denotes the integration time of the image sensor.

The PSF of an imaging system is often modeled as a Gaussian function:

\[
PSF(b, r) = \frac{2}{\pi (gb)^2} \exp\left(-\frac{2r^2}{(gb)^2}\right), \tag{2}
\]

where \( b, r, \) and \( g \) refer to the diameter of the blurred circle on the image sensor, the distance of an image point from the center of the blurred circle, and a constant, respectively.

Fig.2(a) shows 1D profiles of PSFs of normal telecentric system at 5 scene depths between 200 mm and 800 mm from the lens. And the system is assumed to be focused at 400 mm in this simulation. In Fig.2(a), while the PSF at 400 mm appears perfectly focused, PSFs at other depths are out-of-focus accordingly, as expected.

Given equations (1) and (2), the integrated PSFs (IPSFs) of the EDOF system at different depths can be quantitatively determined. We further simulate the IPSFs at the above depths from the lens. The simulated IPSFs are presented in Fig.2(b). The figure shows that the IPSFs of the EDOF visual measurement system are nearly invariant across the above-mentioned depth range. It is to be noted that during the sensor integration, each scene depth is captured under a continuous range of focus settings, including perfect focus. Moreover, a scene depth will be highly focused only for a short duration (due to perfect focus), and severely blurred over the rest of the exposure (due to defocus).

While the IPSF of the EDOF system is depth-independent, a sharp EDOF image \( o(z_0) \) can consequently be reconstructed by deconvolving the captured image \( i(z_0) \) with a single blur kernel, i.e., IPSF:\(^{14}\)

\[
o(z_0) = i(z_0) \otimes^{-1} IPSF. \tag{3}
\]

3. VARIFOCAL TELLECENTRIC OBJECTIVE

The key to achieving extended DOF and depth-invariant magnification in this work lies in (a) the choice of the initial optical system to maintain a constant magnification within its original DOF, (b) the design of the integration strategy of the liquid lens and the initial optical system to maintain a depth-invariant magnification across the extended DOF, and (c) determining the system’s impulse response function, i.e., IPSF, defined in Eq.(1).
In conventional imaging systems, the magnification varies along the depth range. However, for visual measurement, apart from a large depth of field, a depth-independent magnification is also necessary. Therefore, apart from small values of DOF, conventional optical imaging systems fail to meet the magnification requirement of visual measurement as well. Fig.3(a) demonstrates changing magnification in conventional imaging geometry. In Fig.3(a), given two identical objects, the nearer one appears considerably larger on the image sensor when compared with the image of the farther object due to depth-variant magnification. In contrast, a telecentric lens is capable of maintaining a nearly constant magnification. In Fig.3(b), the two identical objects share the same size on the sensor plane, thereby indicating depth-invariant magnification.

In order to ensure a constant magnification, we adopt a bi-telecentric lens in our prototype system. In order to further maintain constant magnification within the extended DOF, a miniature liquid lens is placed at the aperture stop of the telecentric lens. Since the diameter of the liquid lens is larger than the original aperture stop of the telecentric lens, a high SNR value is obtained. Upon changing the focal distance of the liquid lens, the DOF of the telecentric lens correspondingly moves through a depth range considerably greater than the original DOF. Consequently, a blurred image is captured. Further, by filtering with a single blur kernel, the blurred image can be recovered as an EDOF image.

4. EXPERIMENTS

This section presents the experimental results obtained using our proposed system with extended DOF and depth-invariant magnification. In our prototype system, a liquid lens (ARCTIC316, Varioptic) is integrated with a bi-telecentric lens (GCO-231205, DHC). A 1/3” CCD detector is selected as the image sensor. Fig.4 shows the prototype system and its schematic illustration.

In the experiment setup, the two elements to be imaged are placed at different depths. In order to simulate cases under actual application conditions, apart from extended DOF, we also measure the sizes of objects at two
different depths, and we compare the measured values with the ground truth. The original DOF of the telecentric lens is empirically measured to be 50 mm. While numerous approaches have been proposed for deconvolution, including Richardson-Lucy and Wiener deconvolution, a number of techniques also address noises and outliers in deconvolution. In all our experiments, we apply the Wiener deconvolution for convenience, and the IPSF used for deconvolution is obtained by imaging a point light source.

In the experiment, we first place two identical elements away from the lens at 200 mm and 700 mm, respectively. By averagely scanning the focus during a single sensor exposure, a corresponding average-blurred image is captured (shown in Fig.5(a)). It is noteworthy that the two objects span a depth range of 200 mm to 700 mm, which distance is larger than 10 times the DOF of the original normal telecentric lens. Since the IPSF of the EDOF system is invariant to scene depths, the EDOF image can be reconstructed by deconvolving the captured image with a single IPSF. Fig.5(b) shows the deconvolved image with extended DOF. In Fig.5(b), both objects appear focused, thereby indicating that the DOF is extended. It is noteworthy that the extended DOF is as large as 500 mm, which indicates that the original DOF is extended over 10 times. The characters and letters on the two elements are magnified and shown in the insets for a clear view.

The two elements imaged by a normal telecentric lens are also shown in Fig.5(c). While the nearer object (200 mm) appears focused, the farther one (700 mm) is severely blurred. Although a larger DOF can be achieved with a smaller aperture, the SNR will be accordingly sacrificed. Fig.5(d) shows an image captured with a smaller aperture of a normal telecentric lens. The blurred object in Fig.5(c) appears sharper in Fig.5(d) and the DOF seems larger. However, the image becomes very noisy. In contrast, our EDOF image has considerably less noise while both the two objects appear reasonably sharp.

In order to further highlight the image quality of the EDOF system when compared with that of a normal telecentric system with a limited DOF, three solid lines (30 pixels in length) along object edges are marked in Fig.5. These lines are marked on the captured blurred image, the computed EDOF image, and the perfectly focused image, as seen in the figures. The normalized pixel intensities of the solid lines are plotted and compared in Fig.6. The magenta curve of the captured blurry image appears nearly linear. In contrast, the EDOF curve (plotted in red square) has an obvious decreasing step in pixel intensities, indicating a sharp edge. And the perfectly focused curve (plotted in yellow circle) also has a similar decreasing step in pixel intensities; therefore,

*The EDOF image dose show artifacts (such as rings), which is typical of deconvolution.

†All the pictures in the experiment are taken before the same blue background. However, it may appear varied due to different focus settings and camera white balance.
it is particularly noteworthy that the EDOF image produced by our technique is as sharp as the perfectly focused image captured by a normal telecentric system at the edges.

In order to simulate practical application conditions, we further measure the sizes of two objects using our proposed method. Subsequently, we compare the measured values with the ground truth. The ground truth is obtained by using a vernier caliper with an accuracy of 0.02 mm. In the experiment, two different elements are placed at 200 mm and 700 mm from the lens, respectively. Their diameters are measured in the EDOF image by calculating the corresponding number of pixels. The length-pixel metric is determined by measuring the focused object in Fig.5(c). The captured image and the computed EDOF image are shown in Fig.7. The experimental results are presented in TableI.

The results in TableI indicate that nearly constant magnification is achieved via the proposed system over the extended DOF. It is noteworthy that the measured sizes deviate from the ground truth by less than 1%.

The experimental results demonstrate that the proposed technique extends the original DOF by over 10 times. In the extended DOF, size measurement on two objects is conducted. The measurement error is less than 1%, which indicates a depth-invariant magnification. In the computed EDOF images, a few artifacts do exist, and therefore, the EDOF images do not appear as sharp as the perfectly focused images. However, this does not impair the accuracy of measurement, as demonstrated in the experiment. Moreover, we notice in the experiment that when the extended depth range increases, the EDOF images may show further reduction in sharpness. We attribute this to (a) severely defocused PSFs contributing to IPSF integration, caused by a large range of focal sweep and (b) noise in the IPSF due to constraints in experimental conditions when imaging the point light source.
<table>
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<th>Diameter</th>
<th>Ground Truth (mm)</th>
<th>Pixel Diameter</th>
<th>Measured Diameter (mm)</th>
<th>Error (%)</th>
<th>Millimeter/pixel</th>
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</tr>
<tr>
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<tr>
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5. CONCLUSION

In this paper, we present a visual measurement system with extended DOF and depth-invariant magnification. Volumetric optical sampling is applied by rapidly scanning the focus of the liquid lens during a single integration of the detector. The focal plane sweeps through a depth range considerably greater than the original DOF. The liquid lens is integrated into an off-the-shelf bi-telecentric lens, and this integration eliminates the need for hardware modifications when switching between an EDOF and a normal system. The bi-telecentric lens contributes to nearly constant magnification within the extended DOF. An EDOF image can be reconstructed through deconvolution of the captured image and the use of a single blur kernel. In practical applications, the use of a telecentric lens with large DOF is usually very expensive. With our our technique, a large DOF can be obtained by using a considerably less expensive telecentric lens.

As regards future studies in this direction, the IPSF can be more accurately simulated using professional optical software. In the current system, the EDOF image is computed off-line, while in the future, the deconvolution process will be possible to execute on-line, which will lead to fast real-time visual measurement with greatly extended DOF and depth-independent magnification.

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REFERENCES


