### **Experimental Demonstration of capture volume extension for iris recognition systems**

Now we demonstrate the capability of Angular Focus Stacking (AFS) to extend the axial capture volume (depth of field) for iris recognition. We use a Sinar P3 view camera fitted with a 180 *mm* focal length, F/5.6 – F/64, Rodenstock lens and a 50 megapixel, 86H evolution series digital back. The setup is shown in [Figure 5.8](#Figure_5_8). We performed these experiments with an aperture setting of F/8 since it provided an optimal balance between the optical resolution and the instantaneous DOF (which dictates the total number of images required for focus stacking).

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| **Figure 5.8** Setup for demonstrating capture volume extension. We placed three human figure cutouts at 3.429 *m*, 4.038 *m* and 4.648 *m,* measured from the center of the entrance pupil of the lens. Each cutout consists of a 2 *lp/mm* resolution target and a pair of artificial iris of diameter equal to 11 *mm*. We also placed two long aluminum rulers on each side to aid image registration. |

The goals of this demonstration are:

1. To show a substantial improvement in capture volume using AFS.
2. To show that the total time required for capturing all images in the focal stack is less than the exposure time of a single-shot image with equivalent DOF and exposure level.

[Figure 5.9](#Figure_5_9) is an image captured with an aperture value of F/8 in frontoparallel (conventional) configuration. We focused the camera on the middle cutout. Therefore, the 2 *lp/mm* resolution target on the middle cutout is perfectly resolved in the image plane. However, the targets belonging to the far and near cutouts cannot be resolved as they lie outside the DOF region.

The equation for geometric depth of field or the diffraction based depth of focus in the image space requires us to define a circular of confusion or a wavelength respectively. However, here we are interested in a definition of depth of field based on a specified object resolution (2 *lp/mm*). To derive an expression for the DOF (for frontoparallel imaging) as a function of specified object resolution *lp/mm*, we first find an equivalent such that , the Rayleigh resolution criterion in the image. Then, we substitute in the common geometric depth of focus equation to get an expression for the depth of focus. Further, we can obtain the boundaries of the DOF in the object space by applying the Gaussian lens equation to the half depth of focus on either side of the focal plane in the image space. The final expression for the DOF as a function of the specified resolution in the object space is shown below:

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where, is the effective F-number, is the transverse magnification, is the focal length and is the specified resolution in the object space in *lp/mm*. Based on measurements, we have observed that Eq. (5.19) is accurate in predicting the DOF.

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| **Figure 5.9** Single-shot traditional image capture at F/8. The 2 *lp/mm* target on the middle cutout that is in perfect focus can be resolved in the image. However, since the front (left) and rear (right) cutouts are located outside the DOF ( 29 *cm* using Eq. (5.19)), the high frequency information from them are lost in the process of imaging. |

Using Eq. (5.19), and confirmed by observation, we found the DOF for at 4.038 *m* to be approximately 29 *cm*.

In the first experiment, we captured seven images for AFS in increments of between and . The bounding angles were determined such that the plane of sharp focus for the maximum lens tilt, , passes through the eye level of the rear cutout at an angle of about with the horizon, and for the minimum tilt angle, , it passes just above the eye level of the front cutout (see [Figure 5.10](#Figure_5_10)). The value of must be such that when (frontoparallel configuration), the plane of sharp focus, perpendicular to the optical axis, must lie in front of the first cutout towards the camera. Finding the exact values of and is usually an iterative that may be subjected to an optimization algorithm. All images in the focal stack was captured with an open aperture setting of F/8 and exposure time of seconds.

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| **Figure 5.10** In-focus regions in the registered images in the focal stack. The in-focus regions, detected by a LoG filter, are overlaid on the corresponding image in the focal stack. The images were captured with lens tilts: (a) , (b) , (c) , (d) , (e) , (f) , and (g) . Notice how the DOF zone appear to progressively scan the image from top to bottom with increasing lens tilt angle. Also, observe the failure of the current focus measure filter to detect focus in textureless regions. |

[Figure 5.10](#Figure_5_10) shows the focused regions in the images in the focal stack following registration.

From the analytically obtained homography, we observed that the change of transverse magnification between the images in the stack was infinitesimal as expected (using the inter-image homography equation).

The composite image obtained (using the process described previously) is shown in [Figure 5.11](#Figure_5_11)(a) and the corresponding focus measure is shown in [Figure 5.11](#Figure_5_11)(a). [Figure 5.12](#Figure_5_12) shows the zoomed-in portions of regions-of-interest, surrounding the eyes in each cutout, from the composite image. It is evident that the high frequency information from all three cutouts are preserved in the composite image. Thus, in this example, we have demonstrated an improvement in the capture volume from 29 *cm* to at least over 1.22 *m*—a four-fold improvement in the capture volume.

Furthermore, the total exposure time required to capture all seven images in the stack was 5.4 seconds (1/1.3 seconds for each image). A single-shot image capture with equivalent DOF required using an aperture value of F/22. To capture the image at F/22 while maintaining the same exposure level as that of the composite image, the exposure time required was found to be 8 seconds. Therefore, we can see that the total exposure time required for capturing all images in the focal stack is less than the exposure time required by single-shot image capture for the same DOF and exposure level.

To further improve the factor of DOF extension over conventional single-image capture, we moved the set of cutouts (with the separation in-between them intact) towards the camera by 0.61 *m*, such that the new distances to the near, middle and rear cutouts from the entrance pupil center of the lens was 2.82 *m*, 3.43 *m*, and 4.04 *m* respectively. Furthermore, we replaced the 2 *lp/mm*

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| **Figure 5.11** Synthetic image showing extended capture volume using angular focus stacking. (a) The composite image, (b) focus measure of the composite image. The fine features on the artificial irises and the details on the sinusoidal targets are hard to see in this figure owing to the limited size of the display. Please see [Figure 5.12](#Figure_5_12) for zoomed-in view of these regions. |

pattern with a 3.94 *lp/mm* pattern. Per Eq. (5.19) the DOF for the conventional capture should reduce to 12.5 *cm*. Indeed, our observation matched the predicted value of DOF.

The increase in transverse magnification, also affects the instantaneous DOF of images in the angular focal stack. Therefore, to ensure that we do not leave in “focus holes” within the region of interest, we captured fourteen images, tilting the lens from -14.7° to -19°. To improve our chances of obtaining an adequate image of the high frequency target pattern in the presence of the negating uncertainties, we decided to use the commercial software Heliconfocus for blending the images following registration. Figure 5.13 shows a comparison of magnified regions near the eye

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| **Figure 5.12** Magnified view of regions near the eyes in the composite ([Figure 5.11](#Figure_5_11)). Each patch—(a), (b), (c) from the near, middle and far cutouts respectively—occupies equal areas in the image. Despite the noise in the composite image (due to the various uncertainties in the experiment discussed earlier), we can clearly resolve the fine 2 *lp/mm* sinusoidal patterns from all the three cutouts. Therefore, we have demonstrated a DOF of at least 1.22 *m*. Please note that the images were not enhanced in any way. |

from the three cutouts between a single-shot conventional image—(a), (b), and (c)—and the composite image obtained using our method. Due to the slight amount of blurring, display size, and aliasing in the portions of images containing the 3.94 lp/mm pattern, the improvements are not clearly visible. However, we can see that the features in the artificial irises are clearly visible from the three cutout figures. Therefore, in this example, we improved the DOF, or axial capture volume, from 125 *mm* to 1219.2 *mm*—a factor of 9.8 improvement.

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| **Figure 5.13** Comparison of magnified patches near the eyes between the conventional image and composite image obtained using angular focus stacking. (a), (b), (c) are the single-shot conventional images of the eye patches in the near, middle and rear cutouts respectively. (d), (e) and (f) are patches from the same areas in the composite image. |

### **Summary**

We saw that AFS is especially suitable for extending the DOF of iris acquisition systems. We demonstrated the advantages of AFS using two experiments with a Scheimpflug camera. We obtained between 4- and 10-factor of improvements in the axial capture volume over traditional single-shot image capture. At the same time, we showed that the time required for capturing images in the focal stack is much less that the exposure time required using single-shot image capture.