Automated calibration and optical testing of the AWARE-2 gigapixel multiscale camera

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ABSTRACT

Gigapixel-class cameras present new challenges in calibration, mechanical testing, and optical performance evaluation. The AWARE-2 gigapixel camera has nearly one-hundred micro-cameras covering a 120 degree wide by 40 degree tall field of view, with one pixel spanning an 8 arcsec field angle. Viewing the imagery requires stitching the sub-images together by applying an accurate mapping of registration parameters over the entire field of view. For this purpose, a testbed has been developed to automatically calibrate and test each micro-camera in the array. Using translation stages, rotation stages, and a spatial light modulator for object space, this testbed can project any test scene into a specified micro-camera, building up image quality metrics and a registration look-up table over the entire array.

Keywords: Gigapixel Camera, Calibration, Optical testing

1. INTRODUCTION

Gigapixel-class cameras such as the AWARE-2 multi-scale system, present new challenges in calibration, mechanical testing, and optical performance evaluation. These systems are capable of snapshot gigapixel images by using arrays of smaller cameras in a multiscale optical system. The resulting image is a composite from many smaller images, shown in figure 1 from the AWARE-2 gigapixel camera. Forming an image composite based on feature extraction is computationally expensive from such a large data set. In addition, feature extraction may yield invalid points since part of the object field will generally consist of sky or nearby, out-of-focus ground. Therefore, since the AWARE-2 system is a mechanically stable unit, prior knowledge and calibration can be incorporated into the compositing engine, enabling near look-up table performance. Using the proposed testbed, fully automated calibration can be incorporated into the AWARE-2 camera system, enabling faster, higher quality image compositing.

The AWARE-2 Gigapixel camera has nearly one-hundred micro-cameras covering a 120 degree wide by 40 degree tall field of view (FOV), with one pixel spanning an 8 arcsec instantaneous FOV (IFOV). This multiscale system includes micro-cameras focusing on a curved intermediate focal hemisphere imaged by a single, \( f/3.5 \), monocentric objective lens with a 70mm focal length. The 98 identical micro-optics correct for aberrations in the objective lens and demagnify the image to eliminate gaps while relaying the intermediate image plane to the Aptina 14 megapixel, monochrome, CMOS detectors with 1.4 micron pixels. The 98 individual micro-camera images are asynchronously captured to within one-tenth of a second for all the cameras in the array and then stitched into a composite panoramic image. This makes the AWARE-2 system ideal for capturing snapshot, high-resolution imagery of dynamic events.

This paper covers recent advances in an automated, custom testbed system for calibration and performance analysis of the AWARE-2 camera. This testbed enables arbitrary object space features to be projected at any field angle into the objective of the AWARE-2 camera. Modulation transfer function (MTF) data, flat field correction, fiducials for registration, distortion, magnification, and pointing geometry can be programmed into the testbed and integrated into the post-processing of the imaging system.

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Figure 1. The AWARE-2 gigapixel camera system is shown in the bottom right. This camera uses a multiscale design strategy to achieve high optical quality in a low-volume system by implementing a monocentric objective lens and micro-optics for each of the possible 226 focal planes. The camera shown has 98 populated micro-cameras for a combined resolution of one gigapixel.
Figure 2. AWARE-2 camera on the testbed setup. The testbed consists of two 600mm translation stages and two rotation stages (elevation and azimuth). The object space is focused at infinity by using a telescope, which projects an arbitrary image from the mini projector or resolution target. The projector correlates to an area on the micro-cameras of $248 \times 166$ pixels. The source path from either the projector or resolution target follows through the telescope, reflects on the elevation stage mirror, and propagates through the gigagon objective and into the micro-camera optics. The projector is located on the opposite arm of the resolution target, enabling both targets to be used.

2. TESTBED SYSTEM

2.1 Mechanics of the testbed

The testbed system shown in Fig. 2 consists of a two-axis translation stage (X and Z), an azimuth stage mounted on the vertical Z stage, and an elevation stage mounted on the azimuth stage. The translation stages are both Newport Corporation (Irvine, CA) IMS600CCHA units with $\pm 4.5 \mu m$ accuracy, 200mm/sec speed and maximum load of 60kgs. The rotation stages are Newport URS100BCCHA units with $\pm 17 \mu rad$ accuracy, maximum speed of 80$^\circ$/s, maximum load of 30kgs and output Renishaw encoders. The stages are controlled through a Newport XPS-C4 with TCP/IP communication interface. Moving the stage and capturing at the center of a micro-camera takes on average 12 seconds.

The object space target is a spatial light modulator (SLM) by Texas Instruments (Dallas, TX), DLP Pico Projector digital micromirror chip with $7.6 \mu m$ pixels and $480 \times 320$ total pixels. The actual area on the micro-camera detector corresponds to $248 \times 166$ pixels. The projection lens was removed and replaced by an external telescope to form an image of the SLM at infinity. Neutral density filters are mounted in the optical path of the projector with a combined optical density of 4 or 5 since the illumination of the projector is designed for large areas with high brightness. Integration times on the micro-camera are sufficiently long to average over many cycles of the SLM to avoid banding from an unsynchronized rolling shutter on the detector. The telescope and projector assembly are then mounted on a carriage attached to the Z translation stage.

2.2 Alignment of the testbed and AWARE-2 camera

Each time a camera is placed on the testbed it should be able to form images as reproducibly as possible at the same locations in each micro-camera. Using Rodrigues’ rotation formula, the translation and rotation of the camera coordinates to the testbed coordinates can be measured and described by a rotation $\omega_C$ about a unit vector $\hat{n}_C$. The relation between camera and testbed vectors is then described by Eq. 1, where the vector
projected from the testbed is \( \hat{n}_M^{(i)} \) and the image location vector in camera coordinates is \( \hat{n}_R^{(i)} \).

\[
\hat{n}_R^{(i)} = \hat{n}_M^{(i)} \cos \omega_C + (\hat{n}_C \times \hat{n}_M^{(i)}) \sin \omega_C + \hat{n}_C (\hat{n}_C \cdot \hat{n}_M^{(i)}) (1 - \cos \omega_C).
\] (1)

Solving for \( \omega_C \) and \( \hat{n}_C \) requires finding the testbed vector \( \hat{n}_M^{(i)} \) that corresponds to the actual pointing vector \( \hat{n}_R^{(i)} \) that is imaged in the center of each micro-camera. A table of incident rays, \( \hat{n}_M^{(i)} \), and the actual vectors that correspond to the optical axis of the micro-cameras, \( \hat{n}_R^{(i)} \), are built up over the entire array of 98 micro-cameras. The minimum overlap of the vectors \( \hat{n}_R^{(i)} - \hat{n}_M^{(i)} \) determines the optimal \( \hat{n}_C \), given by

\[
L = \sum_{i=1}^{M} w_i \left[ \hat{n}_C \cdot (\hat{n}_R^{(i)} - \hat{n}_M^{(i)}) \right] ^2 = \frac{1}{|\hat{n}_C|^2} \hat{n}_C^T \left[ \sum_{i=1}^{M} w_i (\hat{n}_R^{(i)} - \hat{n}_M^{(i)}) (\hat{n}_R^{(i)} - \hat{n}_M^{(i)})^T \right] \hat{n}_C
\] (2)

which is minimized. This is a Rayleigh quotient with the eigenvectors of the matrix

\[
M = \sum_{i=1}^{M} w_i (\hat{n}_R^{(i)} - \hat{n}_M^{(i)}) (\hat{n}_R^{(i)} - \hat{n}_M^{(i)})^T
\] (3)

corresponding to the stationary values of \( L \) with respect to \( \hat{n}_C \). The minimum overlap for \( \hat{n}_C \) is the eigenvector of \( M \) corresponding to the smallest eigenvalue. Given this solution for \( \hat{n}_C \), the solution for \( \omega_C \) is

\[
\cos \omega_C = \frac{\sum_{i=1}^{M} w_i \left( \hat{n}_M^{(i)} \cdot \hat{n}_R^{(i)} - (\hat{n}_C \cdot \hat{n}_M^{(i)})^2 \right)}{1 - \sum_{i=1}^{M} w_i (\hat{n}_C \cdot \hat{n}_M^{(i)})^2}
\] (4)

with \( w_i \) being nonnegative weights such that \( \sum_i w_i = 1 \), based on the confidence of the measurement \( i \).

Next, the distance from the camera to testbed must be calibrated. This can be done by inputting an approximate value and iteratively finding the correct value by minimizing the intensity variation across the FOV of the camera. This distance only ensures that the rays enter through the camera stop. Image quality will be minimally affected since the object distance is at infinity and the distance is independent of focus position.

The X, Z, and rotation angles of the azimuth and elevation stages are then calculated to correctly project the object space into the micro-camera. The specific geometry and equations will be provided in a subsequent paper.

Projecting coordinate fiducials into the AWARE-2 micro-cameras without a coordinate transform and measuring the corresponding pixel locations on the detectors for two different placements of the AWARE-2 camera yields the distances shown in Fig. 3(b). This error will directly depend on how accurately the camera is placed on the testbed. After the coordinate transform, Fig. 3(a) shows the Euclidean distance error from the two differing placements of the camera. Most of the errors here are from pointing angle errors in the micro-optics, which introduce errors in the coordinate transform.

pixel-to-pixel variation in the gain, offset, and dark noise

3. MEASUREMENT RESULTS

3.1 Modulation transfer function data

Methods of measuring the modulation transfer function (MTF) at the micro-camera image plane such as slanted edge, bar, spoke and sinusoid can be projected using the SLM mounted on the testbed. Due to pixel-to-pixel variations in gain, offsets, and dark noise, a variation of sinusoid measurement was chosen to minimize the affect of the sensor in the optical MTF measurements. To further reduce sensor error, each spatial frequency was measured three times, with a 0, 1/3, 2/3 phase shift. The three recorded frames are: \( I_{ij}^0(k) \), \( I_{ij}^{2\pi/3}(k) \), and \( I_{ij}^{4\pi/3}(k) \), with the superscript indicating the phase of the projected sinusoidal pattern, \( i \) and \( j \) being the vertical
and horizontal pixel number, \( k \) being the spatial frequency. A non-normalized complex-valued optical transfer function can be formed from these three measurements:

\[
A_{ij}(k) = \left| I_{ij}^{0}(k) + I_{ij}^{2\pi/3}(k) \exp(-i2\pi/3) + I_{ij}^{4\pi/3}(k) \exp(-i4\pi/3) \right| \tag{5}
\]

The background estimate function is

\[
B_{ij}(k) = I_{ij}^{0}(k) + I_{ij}^{2\pi/3}(k) + I_{ij}^{4\pi/3}(k) - 3K_{ij} \tag{6}
\]

The samples \( K_{ij} \) give the contribution to the signal due to the dark noise. This can be estimated by measuring several frames with no illumination and averaging the results. A weighted optical transfer function estimate can be formed as

\[
O(k) = \frac{1}{N} \sum_{ij} A_{ij} B_{ij}^{-\gamma} \tag{7}
\]

with \( \gamma \) being an exponent chosen to trade weights between points with high and low exposure and \( N \) being the number of summed pixels.

Results of the MTF measurements using the testbed are shown in figure 4 for 87 micro-cameras at 45 line pairs-per millimeter. This data shows where problems are occurring with the focus mechanism for micro-cameras 106 and 108 and hence severe defocus is dominating the MTF. Additional data for any location on the micro-camera sensor can be measured, building up an entire database of current camera metrics. When dealing with hundreds or even thousands of micro-cameras, automated routines are essential for quality control of the camera during construction and continued monitoring of stability over time.

MTF measurements taken at different locations on a single micro-camera are shown in Fig. 5(a). The MTF drops off quickly near the vignetting point. Replacement optics have been shipped to correct for manufacturing errors in the first design. Prototype micro-optics show an MTF of 92\% at 30\( \ell \)p/mm and 10\% at 350\( \ell \)p/mm, matching well to the aliasing limit of the 1.4\( \mu \)m detector pixels at 357\( \ell \)p/mm.
Figure 4. MTF measurements at 45 lp/mm for 87 micro-cameras at the center of the field for each micro-optic of AWARE-2. The MTF is lower than the designed value because of manufacturing errors. Micro-cameras that show as blue indicate focus calibration is required. The greyed out micro-camera numbers were not measured in this test.

Comparing the performance of the proposed sinusoidal MTF measurement with an ISO 12233 slanted edge method via the commercially available Imatest software (Boulder, CO) is shown in Fig. 5(b). Imatest is a complete software package for optical imaging systems, based off sfrmat by Peter Burns. The slanted edge was captured using an Air Force target edge with back illumination. A flat field measurement of the back-illumination without the target was used to cancel out any illumination non-uniformity. For comparison, the Zemax model MTF corrected for the pixel transfer function (PTF) is plotted. Lastly, the final curve shows the slanted edge MTF result without flat field illumination correction, indicating a slight drop in the low-frequencies. The greatest variation between the methods is in the low-frequencies. Note also that the methods for acquiring the three MTF curves of Fig. 5(b) are completely different and the raw data from each calculation is directly plotted.

3.2 Fiducial measurements for image registration

The array of cameras must appear to the user as a single, continuous image. In the background, compositing engines use coordinates of fiducials measured in the overlap regions of adjacent micro-cameras from Fresnel zone plates projected into the AWARE-2 camera. Fresnel zone plates are used because of the high cross-correlation and speed of computation over large images using the fast fourier transform on a GPU. Raw images are then corrected for distortion and magnification, rotated and translated, and finally fused into a composite image, shown schematically in Fig. 6. For the AWARE-2 camera, thousands of control points can be determined for accurate image composites.

For mapping distortion and magnification, an array of fiducials are projected across the detector in a Cheby-
Figure 5. (a) MTF measurements at 30lp/mm across the micro-camera sensor plane. The center of the field has a much higher MTF while the area near vignetting drops off quickly. Replacement optics are nearly in place that have an MTF of 92% at 30lp/mm across the entire field and drop to 10% at 350lp/mm. (b) Comparison between commercial Imatest MTF calculation and the proposed sinusoidal method for a prototype replacement micro-optic. The Zemax optical model MTF compensated for sensor MTF degradation is shown as the dashed line.

Figure 6. Control points are found in adjacent micro-cameras by projecting Fresnel zone plates into the overlap regions of the micro-cameras. These coordinates are then built up over the entire FOV to populate a look-up table used to register the sub-images.

shev node sampling strategy, minimizing the Runge’s phenomenon—known as ringing at the edges of higher-degree interpolating polynomials. The interpolated polynomials can then be fit to these sampled node points and each pixel can be adjusted to the calibration model over the surface of the detector. The final stitched image is shown in Fig 1, where the image composite has not been corrected for exposure non-linearity. Each image in this composite has a unique integration time, matching the exposure requirements of the micro-camera.
3.3 Flat field measurements

Due to vignetting, the intensity roll-off near the edge of each micro-camera field is significant. In addition, the pixel response is not uniform, therefore, flat field measurements are used to correct the entire field of each micro-camera. This field needs to be taken at the correct entrance angle to match the micro-camera angle, therefore the testbed is ideal for capturing flat field data while measuring system parameters. An example of a flat field measurement is shown in Fig. 7. Pixel statistics of the Aptina detectors require averaging multiple frames to refine the estimate of the flat field.

Flat field measurements are captured at multiple integration times, enabling correct calibration of intensity mapping for HDR composites. This has not be integrated into the registration yet, where errors in the exposure mapping are evident in Fig. 1. The flat field is also used as a round gauge in decenter error of the sensor and micro-optic mounting. Fitting to this circular area, the center of the detector can be mapped to the center of the micro-optic. The testbed can then be used to determine the actual vector that points directly into the micro-camera by iteratively finding the optical axis (which is independent of the flat field image).

A diffuse white LED source was added to the opposite carriage of the projector, shown in Fig. 2. Because of the rolling shutter on the micro-camera, a DC powered LED is ideal. To change the intensity of the LED, a duty cycle can be added at high frequencies, far enough out that the rolling shutter will not be affected. Changing the current of the LED will also change the spectral response of the LED, which in this case is not desirable. This light source is then used for both illuminating targets (such as the 1951 Air Force target shown or in flat field measurements).

3.4 Focus calibration

The telescope on each arm of the testbed requires a collimation check when a new target is attached. This is preformed by using a collimator that is pre-calibrated, with a video-rate detector at the end. When the target is in best focus on the calibration detector, the object space is at infinity. The telescopes are high-f/# systems, making the object position flexible within ±0.3mm. Once calibrated, the infinity focus of the object space can be used to calibrate the micro-camera focus module. The focus range for each micro-camera is 100µm, where 70µm is required for an object distance range of infinity to 15 meters. The extra 30µm of headroom is allocated to the infinity direction to allow thermal and mechanical variability.

4. DISCUSSION

Quality assurance and performance metrics for large scale array cameras promotes many challenges. The wide-FOV and high resolution eliminate standard test procedures, especially when brute force manual measurement for hundreds of cameras is involved. The testbed in this article addresses these challenges with an automated approach that is fully customizable. Examples of MTF, flat field, and image registration are shown, but extensions

Figure 7. Flat field image for a single micro-camera. The roll-off is caused by vignetting while the bright ring is caused by stray light in the first lens element. The decenter error of the detector relative to micro-optic axis is evident as well.
to many other measurements like distortion correction, aberration correction, system alignment, and hardware verification are currently being implemented.

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REFERENCES