Geometric calibration and correction for a lens-coupled detector in x-ray phase-contrast imaging

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Abstract. A lens-coupled x-ray camera with a tilted phosphor collects light emission from the x-ray illuminated (front) side of phosphor. Experimentally, it has been shown to double x-ray photon capture efficiency and triple the spatial resolution along the phosphor tilt direction relative to the same detector at normal phosphor incidence. These characteristics benefit grating-based phase-contrast methods, where linear interference fringes need to be clearly resolved. However, both the shallow incident angle on the phosphor and lens aberrations of the camera cause geometric distortions. When tiling multiple images of limited vertical view into a full-field image, geometric distortion causes blurring due to image misregistration. Here, we report a procedure of geometric correction based on global polynomial transformation of image coordinates. The corrected image is equivalent to one obtained with a single full-field flat panel detector placed at the sample plane. In a separate evaluation scan, the position deviations in the horizontal and vertical directions were reduced from 0.76 and 0.028 mm, respectively, to 0.006 and 0.009 mm, respectively, by the correction procedure, which were below the 0.028-mm pixel size of the imaging system. In a demonstration of a phase-contrast imaging experiment, the correction reduced blurring of small structures. © 2017 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: [10.1117/1.JMI.4.1.013507](https://doi.org/10.1117/1.JMI.4.1.013507)]

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1 Introduction

Previously, nonlinear image distortions in x-ray modalities due to geometric projection factors and optical aberrations from image intensifiers and lenses were corrected by global and local methods or by combinations of both.^{1–16} Recently, grating-based x-ray phase-contrast imaging demonstrated for the first time enhanced detection of tissue structures at a fraction of clinical dose levels using phase gratings exclusively, with off-the-shelf x-ray sources and 200- to 400-nm grating periods.^{17,18} At the same time, lens-coupled x-ray detectors with tilted, front-lit phosphors have been adapted to phase-contrast imaging (Fig. 1). At a shallow beam incident angle of 11 deg onto the phosphor, they doubled the x-ray photon capture efficiency due to light collection from the side of the phosphor illuminated by the x-rays and the increased effective thickness of the phosphor. They also tripled the resolution along the tilt direction when compared with normal-incidence flat-panel detectors due to the extra magnification in that direction.¹⁹ However, the use of wide-angle close-up lenses to improve light collection over a sufficient field of view also introduces inherent nonlinear distortions at large off-axis angles similar to the fish-eye effect of wide-angle photography. Additionally, the tilted phosphor causes distortions in two ways. One is that the geometric magnification of the cone-beam projection varies from the top to the bottom of the image; the second is that nonflatness of the phosphor is magnified by the shallow incident angle and causes image distortion. These three factors combine to cause

geometric warping of the images captured by the lens and camera assembly.

A particular problem arises in current grating-based phase-contrast imaging, where the grating area is limited by fabrication technology. It is often required to scan the sample through a narrow field of view and stitch multiple images, or tiles with partial overlap, into a full-field image (Fig. 1).^{17,20–22} If individual images are geometrically warped, then two types of artifacts appear. The first artifact is created when the tiles partially overlap during stitching, where blurring occurs in the overlapped areas due to misregistration between the tiles. The second artifact is generated when the tiles are stitched without overlap, where seam discontinuity occurs from intertile misregistration.

Here, we describe a calibration and global correction procedure based on polynomial mapping of Cartesian coordinates between the image and a physical plane to correct all distortions in a single step. We applied it to a phase-contrast imaging device, where the sample is scanned vertically through a field of view with substantial overlap between individual images.^{17,18} We imposed a unique condition to be satisfied by the mapping that facilitates vertical tiling of the individual images: the vertical axis of the physical plane aligns with the scanning direction of the sample. The effect of the correction procedure is illustrated in Fig. 2. The scanned trajectories of brass beads in the raw image have an increasing “fanning” appearance from bottom to top and become straight and vertical in the corrected image.

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Fig. 1 A schematic illustrating the lens-coupled, tilted-phosphor detector, and the scanning procedure to form a full-sized image, with the calibration bead phantom as an example. The brass beads (brown dots) are embedded in a polymer cylinder (blue). The cone beam from the x-ray source projects the beads onto the tilted plane of the phosphor. The green light emission from the phosphor is collected by the lens. The lens focuses the light into an image of the phosphor at the sensor chip of a digital camera. The bead phantom is scanned vertically along the Y_w axis in the physical plane, which contains the X_w and Y_w axes. The image plane on the phosphor contains the X and Y axes. A series of images are acquired, while the phantom is scanned in incremental steps. These are tiled together to form a full image. Due to lens aberrations and the tilted phosphor, the acquired image on the camera sensor chip is a geometrically distorted representation of the physical plane.

2 Methods

2.1 Construction of the Calibration Bead Phantom and Measurement of Actual Bead Positions

The phantom was designed to have a linear string of 11 radio-opaque beads of 0.4 mm diameter, spaced at 5 mm (Fig. 3). A 3-D printer was used to produce the form of the phantom due to its flexibility and precision. The 3-D printer (ProJet 3510 HDPlus 3D) had a nominal resolution of 16 μm . The plastic resin material was cured to a rigid form by ultraviolet light. Commercially available brass beads were selected for their small diameters and good contrast relative to plastic under 40 to 70 kVp x-ray radiation. The plastic form was designed to have 11 cavities of 0.4-mm diameter on the surface. The brass beads were heated and affixed into the cavities by displacing the wax support material within.

Fig. 3 A photograph of the bead phantom. The dark dots are the brass beads. They are embedded into a 3-D-printed polymer cylinder. The spacing between the beads is 5 mm.

The relative positions of the beads in both horizontal and vertical directions need to be known accurately in order to calibrate geometric distortions in an imaging system. The actual bead positions were measured by microradiography in a Bruker 1172 micro-CT system, which is equipped with a distortion-free fiber-coupled detector. The brass beads showed strong contrast against the background and were delineated by intensity thresholding (Fig. 4). An ImageJ script was designed to remove disjointed pixels near the border and compute the centroid as the center-of-mass of the remaining mask. This procedure provided relative bead positions in terms of image pixels. To convert image pixels to physical distances, the distance from the first to the last bead was measured with a digital caliper. The conversion factor was thus determined to be 3.64 $\mu\text{m}/\text{pixel}$. In this way, the actual bead positions in two-dimensional coordinates were determined to 10 μm uncertainty. The vertical scan positions of the beads were accurate to 15 μm as described below. These accuracies were sufficient for geometric correction of our system, which had an image pixel size of 28.5 μm in the physical plane, and full-width half-max of the detector point response function (PSF) of 180 μm horizontally and 61 μm vertically as projected onto the physical plane. The PSF was determined by fitting the edge profiles of horizontal and vertical tungsten blade images.¹⁹

Fig. 2 Trajectories of vertically scanned brass beads before and after geometric correction. (a) Before correction, increasing fanning is seen from the bottom to the top due to the tilt angle of the phosphor and lens aberrations of the camera. (b) Geometric correction removes the fanning of the trajectories. The curved shape of the image border illustrates the nonlinear unwarping of the image for the correction.

Fig. 4 Measurement of the actual bead positions was made with high-resolution radiography using a distortion-free x-ray detector and coupled with physical measurements with a digital caliper. An ImageJ script was used to identify the area of a bead by intensity thresholding, illustrated by the red area in the magnified inset. The bead centroid was defined as the center of mass of the masked area.

2.2 Calibration and Geometric Correction of Lens-Coupled, Tilted-Phosphor Detector in a Cone Beam

Referring to Fig. 1, the detector area spans a vertical height of ~ 2.6 mm at the physical plane due to the shallow incident angle of the phosphor, which was ~ 0.08 radians. In a standard imaging procedure, the sample is scanned vertically through the field of view in incremental steps of 0.1 mm. At each step, an image is acquired. The series of images were tiled together with the appropriate vertical offsets and partial overlaps. The result is a full-field image.

The basic approach for geometric correction was to scan the bead phantom across the vertical field of view in the standard imaging procedure, identify the bead centroids in the images in terms of pixels, and determine a polynomial mapping from the bead centroid coordinates in the physical plane in units of millimeters to the coordinates in the image plane in units of pixels (Fig. 1). The physical plane was defined as the plane scanned out by the beads. The mapping was then used to construct geometrically corrected, or unwarped, images in the physical plane. During the calibration scan, the line of beads did not need to be precisely aligned with the X axis of the image plane, and the phantom also has an unknown global offset in the physical plane. These unknowns were part of the polynomial fitting process.

The polynomial mapping from the physical plane back to the image plane may seem backwards, but actually it speeds up the reconstruction of rectangular lattice images in the physical plane. By this mapping, the physical points are mapped into nonlattice points in the image plane. As the raw images are defined on a square lattice in the image plane, it is expedient to find the four pixels in the raw image that surround each physical point and thereby determine the value of the physical point with bilinear interpolation.

The scan direction defines the Y_w axis of the physical plane (Fig. 1). The scanning motor (Kohzu XA05A-L201) has a vendor-specified maximum error of $15 \mu\text{m}$ in the travel direction and $3 \mu\text{m}$ in the perpendicular directions. Together with the measurement uncertainty of the individual vertical offsets of the beads described in the previous section, the vertical positions of the beads were known to $\sim 15 \mu\text{m}$ accuracy. The horizontal positions were known to $10 \mu\text{m}$ accuracy as described in the

Fig. 5 Superimposed two radiograph images of the bead phantom from the calibration scan. There were 11 scan steps, or 1.1-mm vertical scan distance, between the two shots. The beads appear vertically elongated due to the tilted phosphor. Beads 1, 5, and 10 were labeled. The inset is a magnified view of the intensity-thresholded mask delineating bead 10, from which its centroid position in the image plane was determined.

previous section. The bead positions were relative because the offsets between origins of the image plane and the physical plane were unknown. Additionally, the line of beads had a small and unknown slope from the horizontal axis as illustrated by the example images in Fig. 5. The slope was magnified by a factor of 12 due to the tilt of the phosphor. These unknowns were all included in the coefficients of the polynomial mapping that were determined in a least squares fitting.

Measurement of the image plane bead centroid positions is shown in Fig. 5. It shows the superposition of two images taken from the calibration scan at scan steps 12 and 23. The physical vertical spacing was, therefore, 1.1 mm between the two scan positions. The elongated elliptical appearance of the beads was due to the tilt of the phosphor, which stretched the projection in the vertical direction relative to the horizontal direction. The inset illustrates the intensity-thresholded mask of bead number 10. The centroid coordinates of beads in the image plane in units of pixels was determined as the center of mass of the mask. The threshold level was automatically adapted to the local area of each bead image to improve accuracy.

The polynomial fitting procedure is as follows: once the bead coordinates (x_{jk}, y_{jk}) in the image plane in units of pixels were identified, they were expressed as n 'th-order polynomial functions of the relative physical coordinates (x_{wjk}, y_{wjk}) of the beads in units of millimeters, in Eq. (1). The j and k subscripts label the j 'th bead in the k 'th step of the scan. The unknown offsets and slope of the bead line were the zeroth- and first-order coefficients of the polynomials

$$\begin{aligned} x_{jk} &= \sum_{m,n} a_{mn} x_{wjk}^m y_{wjk}^n, \\ y_{jk} &= \sum_{m,n} b_{mn} x_{wjk}^m y_{wjk}^n, \end{aligned} \quad (1)$$

where $m = 0$ to N and $n = 0$ to $N - m$. As the physical Y_w axis is the scan direction, the x_w coordinate of a bead remains constant over the scan

$$\begin{aligned} x_{wjk} &= x_{wj}, \\ y_{wjk} &= y_{wj} + k \cdot S, \end{aligned} \quad (2)$$

where the relative physical coordinates for the j 'th bead (x_{wj}, y_{wj}) were determined in the measurement of actual bead positions described in the previous section, and the vertical scan step S was 0.1 mm. Substituting the values of Eqs. (2) into (1), the polynomial coefficients a_{mn} , b_{mn} were determined by least squares fitting.

Generally, the n 'th-order polynomial fitting has $(N+1)(N+2)$ coefficients to be determined, half from the x expression in Eq. (1) and half from the y expression. Therefore, there needs to be at least this many measurements. A measurement is a measured coordinate of one bead, such as the x or y coordinate of a bead. Each shot of the calibration scan contained 10 beads and provided up to 20 measurements. A fifth-order polynomial fitting has 42 unknowns. Theoretically, three images are sufficient to determine the fit. However, in practice, the beads should sample more positions in the

image to ensure that the polynomial fitting captures the image warping over the entire field of view. In this study, the bead phantom was scanned vertically through the field of view in 0.1 mm steps. From the first image when some beads were in full view to the last image before no beads were in full view, 23 images were included and provided 216 measurements (images in the beginning and end of the scan contained less than 10 beads). The polynomial coefficients were then determined by least squares fitting of Eq. (1).

Recalling that the coordinates in the physical plane (x_w, y_w) are in units of millimeters and the coordinates in the image plane (x, y) are in units of pixels, the dimensions of the detector pixels as projected onto the physical plane were generally expressed as the derivatives ($\partial x_w / \partial x, \partial y_w / \partial y$), which accounts for the cone beam magnification factor and other nonlinear warping effects of the images. At the origin of the physical plane, the projected

Fig. 6 X and Y coordinate maximum excursion measurements pregeometric and postgeometric correction for three beads at the left edge, middle, and right edge of the field of view. Data were from the separate evaluation scan. The correction was based on fifth-order polynomial mapping. (a) X coordinate errors of three beads over all images of the vertical scan, where they were visible before correction. The abscissa is the vertical scan position of the bead phantom. (b) X coordinate errors after geometric correction. Note the 1/100 vertical scale when compared with the graph before correction. (c) The maximum excursions of the x coordinates of the bead centroids were reduced to $6 \mu\text{m}$ by geometric correction. (d) and (e): Y coordinate excursions precorrection and postcorrection. (f) The maximum excursions of the bead y positions were also reduced to $8 \mu\text{m}$.

detector pixel size was expressed by the polynomial coefficients as $(1/a_{11}, 1/b_{11})$.

Once the polynomial coefficients were determined, the geometric correction procedure is as follows: a rectangular lattice in the physical plane of lattice spacing $(1/a_{11}, 1/b_{11})$ was mapped into nonlattice points in the image plane by the backward polynomial transformation of Eq. (1). The value of each physical point was determined from bilinear interpolation among the four surrounding lattice points in the image plane. The rectangular lattice was then compressed into a square lattice of $1/a_{11}$ lattice spacing to give the final corrected image. In our system, the initial rectangular lattice spacing in the physical plane was $(28.5 \text{ and } 2.36 \text{ } \mu\text{m})$, and the final physical image pixel size was $28.5 \text{ } \mu\text{m}$.

The accuracy of the geometric transformation was evaluated with a separate scan of the bead phantom. In the evaluation scan, the phantom was shifted relative to the calibration scan by 2.5 mm horizontally, or half the bead spacing, and 0.05 mm vertically, or half the scan step. In this way, the beads sampled positions that were in between their calibration positions. Images in the physical plane were reconstructed as described previously. The physical bead positions were identified through centroid-finding. These positions (x'_{wjk}, y'_{wjk}) were compared with the known positions in Eq. (2) to compute the errors for the j 'th bead, after removing the uniform offset of the phantom described previously

$$\delta_{x,jk} = x'_{wjk} - x_{wjk}, \quad \delta_{y,jk} = y'_{wjk} - y_{wjk}. \quad (3)$$

The measure of error that is most relevant to the image stitching process is the “maximum excursion,” which is defined for either the x or y coordinate of the j 'th bead over the entire scan as the range from the largest negative error to the largest positive error

$$\Delta_{x,j} = \text{maxover } k(\delta_{x,jk}) - \text{minover } k(\delta_{x,jk}), \\ \Delta_{y,j} = \text{maxover } k(\delta_{y,jk}) - \text{minover } k(\delta_{y,jk}). \quad (4)$$

Although the maximum excursion exceeds the usual maximum error, it represents the maximum possible misregistration if the images were stitched together into a larger image. The position deviations and maximum excursions of all beads were determined for third- to fifth-order polynomial mappings. Examples from the leftmost (number 1), middle (number 5), and rightmost (number 9) beads are given below. The performances of the three polynomial orders were compared by maximum excursions of all beads.

3 Results

Overall, we found global polynomial fitting to be effective for geometric correction. Data from the first-, fifth-, and ninth-beads in the separate evaluation scan are summarized in Fig. 6. In the raw images, the deviation of the bead positions from their physical positions is plotted in Fig. 6(a), and the ones after fifth-order polynomial geometric correction are plotted in Fig. 6(b). The comparison between the x coordinate maximum excursions precorrection and postcorrection is shown in Fig. 6(c). The rightmost bead had the largest excursion of 0.76-mm precorrection, which was reduced to $5.4\text{-}\mu\text{m}$ postcorrection or 0.7% of the precorrection value. Figures 6(d) and

Fig. 7 Comparison of the residual x and y maximum excursions of all beads in the evaluation scan after geometric correction with third- to fifth-order polynomial mappings between image and physical coordinates. There were nine beads in the field of view. The maximum excursions of each bead in the x and y directions are represented in the 2-D graph of Δy versus Δx . The residuals are comparable amongst the three orders.

6(e) show the results for the y excursions. Here, the middle bead had the largest excursion of 0.027-mm precorrection, which was reduced to $8.1 \text{ } \mu\text{m}$ by the correction or 30% of the precorrection value.

Figure 7 shows the comparison among the three polynomial orders. The residual Δy versus residual Δx of all beads in the evaluation scan are plotted for the three orders. There were no statistical correlations between the residuals in the x and y directions. We found comparable residual errors among the three polynomial orders and adopted the lowest third-order polynomial for routine use.

The geometric correction was applied to x-ray phase-phase contrast imaging on a polychromatic far-field interferometer (PFI) consisting of three phase gratings of 399 , 400 , and 400 nm periods placed in between the x-ray tube and the detector.¹⁸ The x-ray tube operated at $40 \text{ kV}/1 \text{ mA}$. The grating size was $1 \text{ mm} \times 7 \text{ cm}$ resulting in an area at the sample position of 5.0 cm in the x direction and 0.7 mm in the y direction. Samples were scanned vertically through the grating area in 0.1 mm steps. The phantom we imaged was comprised of coconut oil as a holding medium and ground eggshells to simulate microcalcifications. A total of 250 scan steps were taken to cover a 25-mm section of the sample. At 2-s exposure per step, the total scan time was 10 min including time for motor movement between shots.

The raw images containing interference fringes were demodulated into attenuation, differential phase, and fringe amplitude maps, which are detailed in Refs. 17 and 18. A complete image representing the amplitude of the interference fringes is shown in Fig. 8. The bead calibration process showed that geometric distortion was strongest in the periphery of the raw images. When the raw images were tiled together with the appropriate vertical overlap, misregistration occurred near the periphery due to the distortion, which resulted in a subtle horizontal blurring effect near the left and right borders of the image. The effect was visible for small features such as a cluster of eggshell bits [left chain of Fig. 8(a)]. The eggshell bits were found to appear sharper after correction when compared with before correction [right chain of Fig. 8(a)]. The visual appearance was corroborated by changes in the cross-section profile across an eggshell particle [Fig. 8(b)].

Fig. 8 A phase-contrast enhanced image of a phantom consisting of coconut oil mixed with ground bits of eggshell to simulate microcalcifications. The image represents the amplitude of the interference fringes, which were attenuated by both intensity attenuation and wave scattering. (a) The progressively magnified views on the left are from uncorrected images and on the right are from corrected images. There appears to be a subtle blurring of the eggshell bits in the uncorrected image when compared with the corrected image. (b) Line profiles across the magnified eggshell bit in (a) show reduced width and increased depth after geometric correction.

4 Conclusion

Efficient detectors are important for x-ray phase-contrast imaging if the benefit of reduced radiation dose is to be realized. At the same time, techniques that utilize linear intensity fringes (either direct or moiré)^{20–24} benefit from high resolution in the direction across the fringes in order to clearly resolve them. Lens-coupled, front-lit detectors with tilted beam incidence onto the phosphor are tailored for this type of imaging, particularly when limited grating size calls for scanning a sample through the field of view and tiling the views into a full-field image. We found that global polynomial transformation is sufficient to correct the geometric distortions associated with this type of detector and remove image blurring in the combined full field from the distortions. The resulting full-field image is equivalent to a distortion-free flat panel detector, which is placed at the sample plane. The pixel x and y dimensions of the corrected image at the sample plane are also precisely known through the calibration process.

In a separate evaluation scan that sampled positions in between the calibration positions of the beads, the residual peak-to-peak position errors were found to be below $9\ \mu\text{m}$ in both horizontal and vertical directions. This was below the image pixel size of $28.5\ \mu\text{m}$ at the sample plane. The residual errors were roughly unchanged for corrections based on third to fifth polynomial mappings. This can be explained by the $15\text{-}\mu\text{m}$ measurement uncertainty of the actual bead centroid positions in the calibration scan, which was determined by the accuracy of the scanning motor.

In our system, the longitudinal extent of the tilted phosphor was 3.6 cm, which was small relative to the wave propagation distances of 40 cm and did not contribute significant variation to the contrast of the interference fringes. Variations in the contrast and shape (period and orientation) of the fringes were always present in the system mainly due to nonuniformity of the gratings. All such variations were corrected with a reference scan. For phase imaging systems in which the longitudinal extent of the tilted phosphor becomes a significant part of the system length, the observed wave interference or propagation effects may vary significantly along the length of the phosphor and needs to be considered in postprocessing.

A limitation of the procedure is that it provides a geometrically corrected projection image in a two-dimensional plane. For CT imaging, a further mapping between the corrected image plane and the 3-D world coordinates is required, and can follow procedures that have been established for cone-beam CT with flat panel detectors.

Disclosures

No conflicts of interest, financial or otherwise, are declared by the authors.

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