Analysis of Image Magnification in X-Ray fan beam Computed Tomography

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Abstract. X-ray computed tomography (CT) is a non-destructive measurement method that allows inspection into both external and internal geometry of a scanned sample. This work is mainly concerned with industrial X-ray CT and its 2D image reconstruction parameters. The purpose of our study was to investigate how image magnification in 2D X-ray CT is influenced by the object position for a 50.5 mm x 50.5 mm cuboid. Using a standard definition of magnification, equations were derived to enable geometrical magnification to be determined from its position and vice versa knowing the diameter and machine parameters. Experimental data are compared and observed with regard to geometrical magnification. Results from experimental data showed a strong correlation between geometrical magnification and image magnification obtained from the reconstructed CT image. Derived sizes of cuboid from magnification were more consistent horizontally with geometrical magnification than vertically.

1. Introduction
Computed Tomography (CT) can provide a 2-D or 3-D cross-sectional view of the interior of a sample by transforming X-ray transmission data collected by an array of detectors at varying angles into a reconstructed image of sample’s interior. CT scanning process can be done within a few minutes with the availability of advanced radiation detector system and high-speed computers. The projections or slices enable us to obtain visual information that is hidden from our sight including internal geometry. X-ray CT is commonly used in the process industry to inspect samples with different properties like metals and non-metals, objects with smooth and irregular surface, or dense and low dense object.

The X-ray CT system does not provide data on the accurate dimension of an object in terms of SI base units viewed in the cross-section image reconstructed from X-ray projection data. These data are important for the CT operator to make an assessment of the size of the holes and defects in an inspected sample as well as the severity of damages. However, information on parameters such as size, volume, and density of an object including any defects can only be obtained by taking into account the image magnification. This paper describes experiments conducted to analyze the influence of geometrical magnification on the size reconstructed CT image. Both variables depend heavily on the position of sample relative to the detector arrays and X-ray source. The comparison between the dimension of the real sample and CT image was also done. One way to do this is by placing a sample
with known dimensions at an optimal distance from the X-ray source preferably at the center of rotation (COR) to reduce artifacts and sharpen the CT image. The estimation of a sample size from the CT image is obtained from the product of image magnification and the actual size of the sample.

Two different methods have been used historically to solve the problems connected with image magnification. The first was to develop a mathematical theory on geometrical magnification on computed tomography dimensional measurements. The second experimental approach was to use calibration objects with which to calculate magnification at some points on the image (Yuan, 2013). The second approach is described in this paper along with the basic optics equation for image magnification for comparison. The scope of this paper is to focus on the image magnification in a horizontal and vertical direction from the X-ray source and how it was affected by the object’s position.

2. Materials And Methods

2.1. X-ray CT System

The X-ray CT system composed of:

a) X-ray source: The energies of X-ray are adjusted depending on penetrability or density of samples. The maximum energy and current for this system is 160 kV and 10 mA. To produce a useful X-ray fan beam, a lead collimator is placed in front of the X-ray source.

b) X-ray detector: The X-ray detector (linear array detector) is assembled in a metal casing that is installed with collimator and scintillator material mounted on the surface of an array of the photodiode. The LAD has a good spatial resolution from a small pixel size of 0.4 mm (height) x 0.4 mm (width). The calibration of the detector elements is performed before the initiation of the linear array detector (LAD).

c) Mechanical stage: 50.5 mm x 50.5 mm wood cuboid sample is chosen to be inspected and placed on top of the rotation table during the experiment. The rotation table can be moved up, down, front and back from the detector and X-ray source. The scanning data are acquired during rotation by computer software (LabView). Sample scanning took less than 2 minutes and image reconstruction is done in less than 4 minutes.

Figure 1. 50.5 mm x 50.5 mm wood cuboid sample
2.2. Geometrical Magnification

For 2D cross section X-ray CT image we define magnification as:

\[
\alpha = \frac{\text{Image length}}{\text{Object length}}
\]

and

\[
\beta = \frac{\text{Image width}}{\text{Object width}}
\]

as horizontal and vertical magnification. The benefit of using \( \alpha \) and \( \beta \) as defined above is that we can directly calculate magnification from the object dimension and the use of computer software without calculating the object position. Geometrical magnification is defined mathematically as the ratio of source-to-detector distance (SD) to source-to-object distance (SO). By placing the wood sample closer to the X-ray source, the larger resolution can be obtained, but at the same time, the CT image will be less sharp. SD is kept constant and SO is the only variable manipulated throughout the experiments. (Amalija Horvatić Novak, 2016).

\[
\text{Geometrical Magnification} = \frac{SD}{SO}
\]
The horizontal and vertical dimension of the wood sample was measured on the reconstructed CT image by using Image-J software. These two parameters will be compared with the actual dimension of the sample and analyze the changes in geometrical magnification. This paper will focus on both horizontal and vertical magnification although both variables may not follow the same basic principle for image magnification. Table 1 presents the scanning parameters set for all seven cases while in Table 2 are given SO and calculated values of geometrical magnification as stated by equation 3. The closer the object to X-ray source the larger the resolution that can be achieved. Geometrical magnification usually has an inverse relationship with SO in the standard CT system. In this paper, wood cuboid with dimension 50.5 mm x 50.5 mm is investigated to observe the changes in α and β with geometrical magnification and also a deviation from a mathematical prediction that comes with it.

Table 1. Scanning Parameters

| Parameter           | Amount |
|---------------------|--------|
| Voltage, kV         | 120    |
| Current, mA         | 2.5    |
| No. of Projection   | 1352   |
| Detector Size, mm   | 0.4    |
| Pixel Size          | 100x1450x10 |
| FOC                 | 1.0    |
| Source-to-detector  | 1000   |
| Distance (SD), mm   | 1000   |

Table 2. Source-to-Object Distance (SO) and Geometrical Magnification

| Parameter               | Experiment No. |
|-------------------------|----------------|
|                         | 1   | 2   | 3   | 4   | 5   | 6   | 7   |
| SO, mm                  | 400 | 450 | 500 | 550 | 600 | 650 | 700 |
| Geometrical Magnification| 2.500 | 2.222 | 2.000 | 1.8181 | 1.667 | 1.538 | 1.428 |

3. Results and Discussion

Figure 4. Reconstructed X-ray CT images of wood sample. Right and left represent SO = 400 mm and 700 mm respectively.
Figure 5. Reconstructed X-ray CT images of phantom cylinder. Right and left represent SO = 400 mm and 700 mm respectively. Diameter of holes 1, 2, 3, 4, and 5 are measured.

Lengths of the wood cuboid in Figure 3 are measured from left to right while widths are measured from above to below. The procedure is repeated for all seven images obtained. The results are shown in Table 3 including geometrical magnification, α, and β. The comparison α and β are observed and the pattern is shown in Figure 4. Deviation of α and β from predicted values are calculated.

Table 3. Comparison between geometrical magnification, length and width of the wood sample measured by ImageJ software, calculated α and β, and respective deviations from geometrical magnification.

| SO, mm | 400 | 450 | 500 | 550 | 600 | 650 | 700 |
|--------|-----|-----|-----|-----|-----|-----|-----|
| Geometrical Magnification (SD/SO) | 2.5 | 2.222 | 2 | 1.818 | 1.667 | 1.538 | 1.428 |
| Length (pixelsx0.4cm) | 124.4 | 111.2 | 100.8 | 92 | 84.8 | 78.4 | 72.8 |
| Width (pixelsx0.4cm) | 124.8 | 112 | 101.2 | 92.4 | 84.8 | 78.8 | 73.6 |
| α (Length from image/Object’s length) | 2.46337 | 2.20198 | 1.99604 | 1.82178 | 1.67921 | 1.55248 | 1.44158 |
| α deviation from geometrical magnification | -0.0366 | -0.02 | -0.004 | 0.00378 | 0.01221 | 0.01448 | 0.01358 |
| β (Width from image/Object’s width) | 2.47129 | 2.21782 | 2.00396 | 1.8297 | 1.67921 | 1.5604 | 1.45743 |
| β deviation from geometrical magnification | -0.0287 | -0.0042 | 0.00396 | 0.0117 | 0.01221 | 0.0224 | 0.02943 |
Figure 6. Measured $\alpha$, $\beta$, and geometrical magnification of wood sample form almost inverse relationship with the increase of SO.

Figure 7. Deviation of $\alpha$ and $\beta$ from geometrical magnification for wood sample.
### Table 4. Diameter of holes 1, 2, 3, 4, and 4 of phantom cylinder with different SO

| Position | 1   | 2   | 3   | 4   | 5   |
|----------|-----|-----|-----|-----|-----|
| 40       | 8.300 | 7.983 | 7.113 | 6.338 | 5.038 |
| 45       | 7.417 | 7.113 | 6.200 | 5.663 | 4.513 |
| 50       | 6.688 | 6.525 | 5.600 | 5.158 | 3.981 |
| 55       | 6.188 | 5.875 | 5.167 | 4.642 | 3.713 |
| 60       | 5.638 | 5.433 | 4.792 | 4.283 | 3.438 |
| 65       | 5.258 | 5.000 | 4.442 | 3.988 | 3.200 |
| 70       | 4.867 | 4.667 | 4.100 | 3.694 | 2.919 |

### Table 5. Comparison between geometrical magnification, horizontal and vertical diameter measured by ImageJ software, calculated α and β, and respective deviations from geometrical magnification.

| SO, mm | 400  | 450  | 500  | 550  | 600  | 650  | 700  |
|--------|------|------|------|------|------|------|------|
| Geometrical Magnification (SD/SO) | 2.5000 | 2.2222 | 2.0000 | 1.8180 | 1.6670 | 1.5380 | 1.4280 |
| Horizontal diameter (pixelx0.4cm) | 32.2808 | 29.0204 | 26.2932 | 23.8856 | 22.0812 | 20.4420 | 18.9600 |
| Vertical diameter (pixelx0.4cm) | 32.1620 | 28.8180 | 26.2492 | 23.8432 | 22.0408 | 20.3600 | 18.9616 |
| α (Horizontal diameter from image/phantom's diameter) | 2.5023 | 2.2496 | 2.0382 | 1.8516 | 1.7117 | 1.5846 | 1.4698 |
| α deviation from geometrical magnification | 0.00239 | 0.0276 | 0.0382 | 0.03359 | 0.04472 | 0.0466 | 0.0418 |
| β (Vertical diameter from image/phantom's width) | 2.4932 | 2.2339 | 2.03482 | 1.8483 | 1.7086 | 1.5783 | 1.4699 |
| β deviation from geometrical magnification | -0.0068 | 0.0119 | 0.0348 | 0.0303 | 0.0416 | 0.0403 | 0.0419 |
Figure 8. Measured $\alpha$, $\beta$, and geometrical magnification of phantom cylinder form almost inverse relationship with the increase of SO.

Figure 9. Deviation of $\alpha$ and $\beta$ from geometrical magnification for phantom cylinder.
Figure 10. Measured magnification of holes 1, 2, 3, 4, and 5 in phantom cylinder that form almost inverse relationship with the increase of SO

The length and width of wood are measured from reconstructed CT images by using the application in ImageJ software. From the magnification formula (3), it is logical to assume that with the increase of source-object-distance (SO), the closer the distance between sample and LAD, and size of the sample will decrease inversely approaching the actual size of the sample. Results presented in Table 3, 4, 5 and Figure 6, 7, 8, 9, and 10 show a decline in the amount of magnification almost reciprocally with the increase of SO distance. Measured lengths decline with an increase of SO until the SO reaches 1000 mm which is SD (magnification = 1). Deviations of magnification between the reconstructed image and geometrical magnification are caused by measurement errors or the magnification formula needing varying position in geometrical cone beam taken into account. From the result, it can be concluded that the horizontal and vertical magnification values measured experimentally by scanning sample with varying horizontal position seem to be in fine agreement with geometrical magnification calculated from theoretical calculation at a SO of 400 mm to 700 mm from. The dimension of any computed tomography samples can be inferred directly by dividing image size with the geometrical magnification. From Figure 7 and 9, it can be observed that the biggest deviation in magnification occurs when the sample is farthest or nearest from the X-ray source. Most precise magnification can be obtained when the sample at around 500 mm which is middle ground from X-ray source and LAD for wood sample. For phantom cylinder, which is larger than wood sample, should be placed near 400 mm from X-ray point source to get more precise measurement.

4. Conclusion

In this paper, the characteristics of dimensional measurement are examined carefully by focusing on the magnification parameter so we can analyze the changes of the object’s dimension with its position measured in CT images. Horizontal and vertical magnification are analyzed together to see whether they both differ in characteristics with the changing object’s position. The results obtained show both parameters are in close agreement with the theoretical prediction (or geometrical magnification in this case) for wood sample. Although observed carefully, small deviations occur and show the largest amount when the object is near LAD and near X-ray source. For phantom cylinder, more precise
analysis is needed for varying position and geometrical shape in cone beam geometry. The deviation may also be caused by the fact that the beam may not be strictly cone-shaped as we thought. A further step in the research for dimensional measurement in X-ray CT should include the assessment of measurement uncertainty and also thorough mathematical discourse by taking X-ray beam geometry into consideration.

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