Positional Stability of 2D X-ray Images for Computer Tomography

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Abstract. Recently X-ray Computer Tomography (XCT) has made its introduction in the 3D geometrical quality control of industrial parts. The step from medical to industrial CT recommends a much higher accuracy of the CT process. Part of the accuracy is determined by the accuracy of the 2D radiographic images used to digitally reconstruct the scanned object. This paper discusses a method for improving the stability of the 2D X-ray image position. This method is than tested on an industrial part, on a 225 kV CT machine. The positional stability is mainly influenced by the spot stability of the X-ray source. This spot can drift due to wear of the target or heat fluctuations inside the source. The compensations of the drift of the 2D images are on one hand based on temperature measurements of the X-ray source and on the other hand based on calibration spheres measured together with the part. The techniques used in this paper can be applied to any 3D X-ray CT scan and are easy to implement. To conclude a comparison is made between the original scan of an industrial part and the compensated scan to give an idea of how much this stability influences the whole scanning process. This paper gives a better insight into some errors occurring during the X-ray CT process and can contribute to the accuracy improvement of the XCT process.

Introduction

Until a couple of decades most geometrical metrology instruments didn't allow internal 3D measurements of parts or assemblies in a non-destructive manner. Ever since some non-destructive testing techniques for analyzing internal structures have been commercialized and used by the industry to validate part quality. XCT is one of these techniques and is useful to perform 3D geometrical measurements on assemblies, complex structures as well as the inner geometry of parts made by additive manufacturing, as described by J.P. Kruth et al. [1]. However the accuracy and applicability of CT-based measurements remains uncertain, due to influencing factors related to the workpiece, the CT equipment, the set-up, operator decisions [2] and the reconstruction software.

An overview of the influencing factors and improvement strategies has been worked out by F. Welkenhuyzen et al. [3], here the most important factors influencing CT performance are classified, using the basic components of the CT system as a starting point. Some of these influencing factors have been investigated based on simulations. The effect of source pre-filtration, alignment accuracy and detector exposure time [4], magnification, instabilities of voltage and position of the work piece [5] can be found in literature. Others have investigated the orientation of the work piece, magnification and number of projections [6], alignment of the scanner geometry and the edge detection method [7][8] on an experimental manner..

One of the important influencing factors is the interaction between the hardware settings and the data processing. Correct information about the source to workpiece and source to detector position are crucial in order to generate a correct reconstruction. Errors generated in the hardware setup are taken along into the following steps in the XCT process. Thus the stability of the X-ray-source will be important for maintaining stable X-ray images. As the focal spot will begin to drift, the projection of the scanned object onto the detector will be influenced, which will eventually result in errors in the reconstruction (if no compensation is executed). This paper focuses on compensating the drift of the focal spot to improve the reconstruction and can contribute improving the accuracy of XCT.

Before improving the positional stability of 2D X-ray images used for CT purposes, this paper investigates the magnitude of the drift in the 2D images. Many industrial XCT scanners use images of an object rotated over 360°. Ideally an X-ray image taken at 0° and one at 360° (exactly one rotation) should give exactly the same result. In reality this is not always the case. In case of very long scans it is even possible to visually see shifts in the gray values and shifts in the position of the image without zooming into pixels or using software enhancement. This paper focuses on the positional variation of radiographic images used for CT purposes. The shifts in gray values won't be discussed in this paper. Later on some methods for compensating the drift of the focal spot are suggested and one of these methods is implemented on an industrial case study.

Analysis of the Positional Drift of the X-ray Spot

1.1 Set up of the Experiments

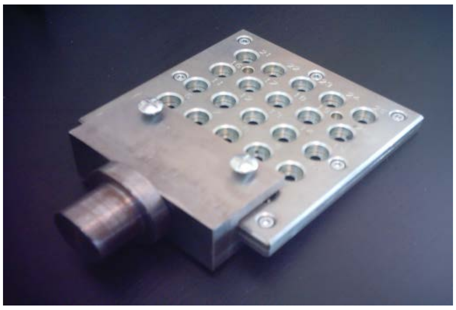

Figure 1 Clamped holes plate [9][10]

Figure 2 Exploded view of the hole plate clamping

To examine positional drift, a holes plate, as used for calibrating optical and tactile coordinate measuring machines, was used (Figure 1, [9] and [10]). The plate was mounted on the rotary table where normally the scanned piece would be positioned. A representation of the mounting of the holes plate inside the XCT machine is shown in Figure 3. The holes plate consists of two thick plates which support a thin plate in between. The thin plate has a thickness of about 1 mm and contains calibrated holes, which will be measured. To mount the holes plate, a steel U-shaped clamp was used. The clamp is connected with an overture made shaft which is secured in the hole of the rotary axis in which the rotary table is normally mounted, as shown in Figure 2. Once the holes plate is mounted, the plate is rotated approximately parallel to the detector. This had to be done manually on sight because the used XCT machine didn't have any image processing software to search for the most parallel position.

To get a better insight on how drift caused by temperature variations is manifested inside the XCT machine, temperature sensors where mounted inside the XCT machine. Three sensors were mounted, one at the X-ray source, one on the holes plate and one on the detector. The sensor on the holes plate will also be used to compensate for any temperature fluctuation of the hole plate. If the temperature of the holes plate would rise, the holes plate would also expand, so instead of measuring drift of the image, the expansion of the holes plate would be measured. Temperature changes of the source and detector could explain drift which is caused by the XCT hardware. For measuring the temperature, 10 kΩ NTC resistors where placed in serial connection with 10 kΩ resistors over 5 V DC voltage, creating a prescaler, so the temperature could be derived from the measured resistance of the NTC's. To reassure the thermal contact between the NTC and the components, a thermal conducting paste was used between the NTC's and the surface to which they were attached.

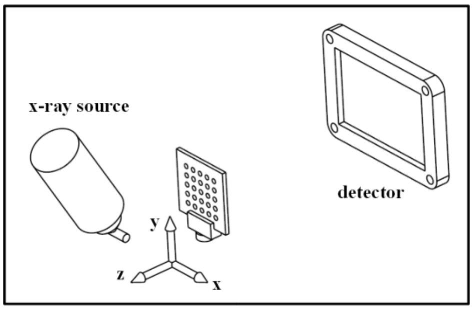

Figure 3 Setup of the holes plate inside the XCT machine

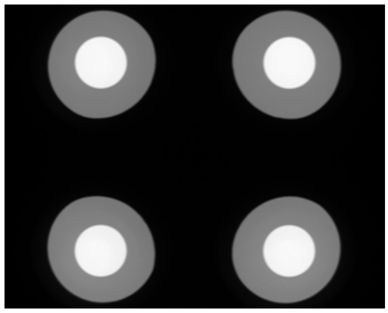

Figure 4 X-ray image of the 4 measured holes of the holes plate

Four holes of the holes plate where put into the frame, by manipulating the magnification axis and the x- and y- axes of the XCT machine (see Figure 4). The reason for only measuring four holes and not the entire holes plate is that measurements could be performed at a higher magnification, which would make drift of the focal spot easier to detect. The detector used on this machine has 1536 rows and 1918 columns of pixels and a pixel size is 97 µm.

After the mounting of the holes plate, the XCT machine was turned on for one hour, during which 2D X-ray images were taken of the stationary holes plate, with a frequency of 1 image per minute. The images show 4 holes, the positions of these 4 holes where later on measured to see whether or not the holes would stay on the same point or move over a certain period of time. After the period of one hour the machine was turned off for one hour to cool down. This process was then repeated two or three times, and repeated on several days. After this the created radiographic images where processed.

To determine the positions of the four holes on the 2D images the holes were measured as circles. At first, regions of interest are selected on the images were an algorithm searches for a hole. Then each row and column of gray values is represented as a series of numbers. These series are numerically derivated and peaks in the derivative are detected as edges, thus creating a maximum gradient edge detection. These pixels are used to make a first estimation of the position of the hole, by fitting a circle through the selected pixel positions. This is still a rough method for determining the hole position, for defining the hole positions more precisely an iterative approach is used. The previous hole position (the centre of the fitted circle) gave a position <x1;y1>, this position was then used as starting point to determine the search directions for finding the edge of the hole more precisely. Again the maximum gradient (peak values in the derivative) in gray values was searched for, with the exception that the search started in point <x1;y1> and the direction went from 0° to 360° in steps of 1°. So the algorithm starts at point <x1;y1> under 0° searches for the maximum derivative in the direction away from the centre <x1;y1>, searches under an angle of 1°, then under an angle of 2°, and so on. While this is done the images also undergo pixel interpolation. This was done because there is no idea how big the shift of the images would be: if the images would shift less than a pixel, there could be a risk that no significant shift would be recorded. The pixels were interpolated one tenth of the pixel size by means of a bicubic spline interpolation, a method frequently used to interpolate pixel of images. The outcome of the maximal deviation positions is again used to fit a circle using the same least squares algorithm from the first rough fit. The positions of these circles gave us the positions of the holes in the different images.

1.2 Results of the Experiments

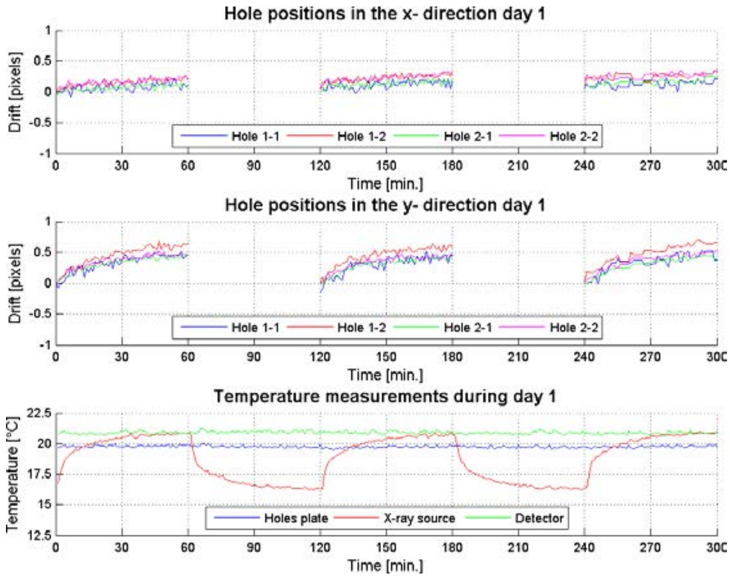

Figure 5 Drift of the 4 holes on the 2D X-ray images and temperature measurements

The experiments were done with a source voltage of 70 kV and 150 µA. These parameters were chosen because they gave the best contrast between air and the holes. Figure 5 is an example of a measurement during one day. The start positions of the holes are taken as reference positions and are set to <0;0>. When the source is turned off there are no measurements for the positions of the holes. The unit of the positions is pixel size, so a shift of one pixel size would mean that the image is shifted one pixel, which means the projection of the radiographic image has shifted 97 µm. The radiographic image taken by this XCT machine is actually an enlargement of the true holes plate, because this machine works with a conical X-ray beam. The enlargement can be calculated based on the source to detector distance and source to scanned object distance. For this experiment the holes plate was placed at 180 mm from the source and the source to detector distance is 1024 mm. This would mean that the drift of 1 pixel represents an actual drift of the measured object of 17 µm (= 180 / 1024 * 97 µm).

The top two graphs of Figure 5 show the measured drift of the holes in x- and y- direction. The lower graph of Figure 5 shows the temperatures of the source, holes plate and detector. The temperature of the holes plate and the detector stays more or less constant and doesn‘t differ more than 2 °C over an entire measurement day (300 minutes). The biggest temperature difference is measured at the X-ray source. This was expected because less than 1% of the power generated by the source is converted into X-rays while the rest is mainly converted into heat [11]. The XCT machine used for this experiment applies water cooling for the X-ray source and the detector. It's clear that the temperature rises when the source is turned on and stabilizes after a certain period of time. When the source is turned off, the source cools down again and the temperature goes down to its original value.

When the x- and y- positions and the temperatures are compared over the different days, the same trend seems to return except for the x- position. A possible cause for this trend is discussed later on. The y- positions of the holes, like the source temperature, seem to rise very quickly in the beginning but stabilizes after a certain period of time. The positions of the holes also seem to move in the same direction for the x- and y- position, as shown in Figure 5 and Figure 6. So the positions of the 4 holes are moving in the same direction and at the same rate. This is also confirmed by the distance between the holes, which remains constant except for some noise.

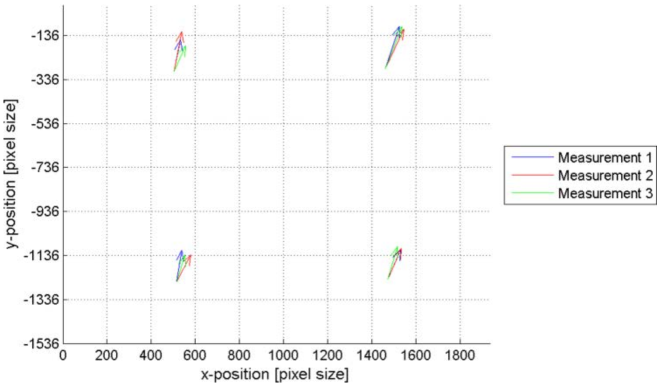

Figure 6 Direction of movement of the holes inside the X-ray image

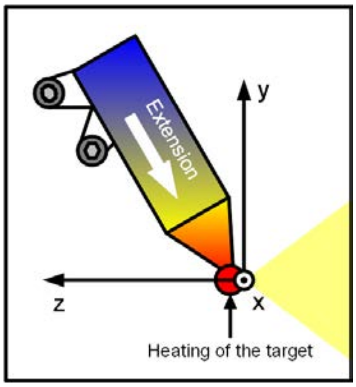

Figure 7 X-ray source mounting

The most significant drift in position is in the y- direction. This is most likely due to the mounting of the source, as shown by Figure 7. The easiest way to represent the source is by a cylinder. The centerline of this cylinder is positioned in the yz- plane and has an angle of 70° with the z- axis, as represented in Figure 7. At the bottom there is the target where the X-rays are produced and most of the heat is generated inside the source. The other end of the source is mounted to the frame of the XCT machine. So when the source is turned on it will expand due to the heat that is induced at the bottom, causing the spot to shift downwards. This will cause upward shifts of the radiographic images in the y-direction. The drift in x- position is probably due to the asymmetric alignment of the filament. The images always seem to shift to the left except for the first measuring day. This could be explained by the fact that the filament was changed between the first and the second measuring day, causing a different alignment of the filament over the days.

Two important statements can be made based on these experiments. Firstly that drift does exist on the tested XCT machine and that it is a repeatable phenomenon. Secondly that there is a significant temperature rise at the bottom of the X-ray tube (where the target is positioned) when the source is turned on. The drift which is mainly manifested in the y-direction could be explained by the combination of mounting and thermal expansion of the source.

Practical Implementation of Positional Drift Correction

Previous experiments show that it is possible to monitor positional drift of radiographic images used for CT purposes. This section discusses some methods how to compensate for the drift of XCT images to create a more accurate voxel model.

There are three obvious solutions on how positional drift compensation can be implemented in the XCT process. As first method, previous measurements can be used for compensating future measurements. This way the previous measurements would become calibration measurements for the positional shift. Because the previous measurements were all conducted at 70 kV and 150 µA, other settings would probably influence the positional drift of the radiographic images. As for instance a higher power demand would induce more heat in the source and cause the source to expand more or with a different trend. Repeating these measurements at different settings would be very time consuming and there is no real time check of the positional drift during a measurement of a part.

A second method would be to search for a mathematical link between the temperature measured at the source and the drift. This method has the advantage that it is easy to monitor the temperature. Some commercial XCT scanners are standard equipped with heat sensors. This method however has a few downsides. It would require repeating the drift measurements with different settings, what would cost a lot of time and effort. Furthermore would any other phenomena which could influence the positional drift be neglected.

A final option for compensating the positional drift is to measure some stationary points together with the object being rotated inside the XCT machine. This would be the best option as the positional drift is measured on the images itself, so any fluctuations which wouldn't be directly linked to the settings or the source temperature would also be recorded. This method can be used for any settings on the XCT machine. Unfortunately the holes plate used in previous tests is to large and would block the view of the object. Therefore two steel spheres were used which were placed inside the field of view of the detector at the sides of the scanned object. The spheres were supported by arms which are placed next to the rotary table (Figure 8). This way they don't rotate along with the object. So when the 2D X-ray images are taken over 360°, two spheres show up on every image, as demonstrated by Figure 9. The position of the spheres inside the image can be measured, using the same algorithm used before to measure the holes of the holes plate. The first measurement points can be used as a reference, if the other measured points drift, these points can then be used to counter shift the images.

Positional Correction of 2D Images on an Industrial Case Study

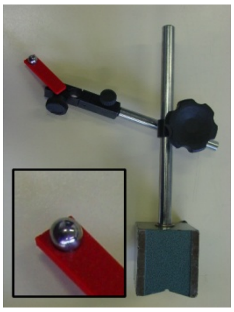

Figure 8 Sphere holder with socket

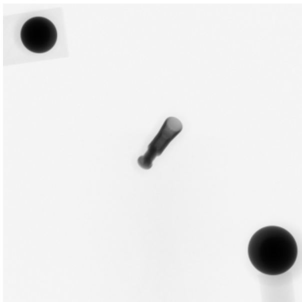

Figure 9 X-ray image of the case study with spheres

To conclude the research, the last method to improve positional stability was applied on an industrial case study. The part is a few centimetres in height and has a maximal diameter of 5 millimetres, no complete specifications can be given due to confidentiality reasons. To clarify a CT reconstruction is given in Figure 12. The advantage of such a small part, for testing the efficiency of the drift compensation, is that it can be scanned close to the source, so drift of the source is more magnified. As suggested in the previous paragraph, some stationary points need to be measured to detect positional drift. In this case two steel spheres with a diameter of 8 mm were used. Each of these spheres where supported by a polymer (ABS) socket and a steel arm, as shown in Figure 8. The ABS socket is long enough, so the steel isn't visible on the X-ray images. A polymer socket was chosen because it creates a sufficient contrast on the X-ray image between the steel sphere and the socket, this way the socket won't interfere with the algorithm filtering out the spheres. One of the spheres was mounted in the upper left corner and the other in the lower right corner of the measuring volume, as shown in Figure 9.

For the case study a scan with 3143 images was performed. Each image contains two circular spots from the spheres. The scanning of this part was performed on a different machine as used for the previous tests. Due to practical reasons no thermal sensors could be fixed inside this machine, so no temperature data is observed during these experiments.

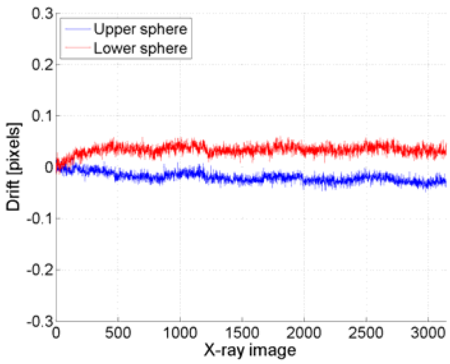

Figure 10 Shift of the spheres in x- direction

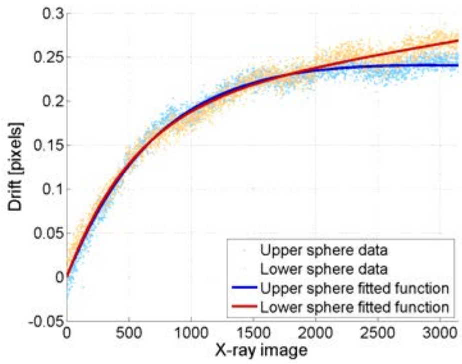

Figure 11 Shift of the spheres in y- direction

The projection of the spheres on the 2D X-ray images were measured as circles, by using a similar algorithm used to measure the hole positions in the first set of tests. In Figure 10 and Figure 11 the x- and y- shifts of the two spheres are shown. The scan is taken with the object positioned at 191 mm from the source, a source to detector distance of 1143 mm and a physical pixel size of the detector of 200 µm. So a shift of one pixel would represent a shift of 33 µm at the position of the object. The first position is again used as reference position and set to <0;0>. A trend similar to the tests with the holes plate is observed for the y- positions. For the x- positions the spheres seem to move away from each other, causing them to move closer towards the edge of the image. This could again be explained by the expansion of the X-ray tube. This would cause the spot to move lower and closer to the measured object, which explains the shift of the spheres to the outside of the image. Because the direction of shift of the spheres in x- direction was opposite and negligible small (less than 0,05 times the pixel size), the decision was taken to only compensate for the drift in the y- direction.

The measured y- positions aren't used right away to shift the 2D X-ray images because they are noisy and a slight difference in trend between the upper and lower sphere is observed. Therefore a function was first fitted onto the data of the upper and lower sphere, see Figure 11. This would smoothen the trend and reduce the noise on the measured y- positions. The fitted function is given by Formula 1. The mean of the 2 fitted curves is then used to shift the X-ray images.

$$y(t) = A\left(e^{\beta_1 t} - e^{\beta_2 t}\right)$$ **Formula 1**

The X-ray images are shifted by using a bicubic spline interpolation. This method for shifting images causes a slight smoothing of the pixel values. A better way to compensate for positional drift would be to shift the images during reconstruction in the reconstruction software. Unfortunately this was not possible because of the use of commercial software. Two image stacks where generated. One image stack was only cropped to prevent the spheres to interfere with the reconstruction. Another image stack was first shifted based on the measured positions of the spheres and then cropped.

Two 3D reconstructions were made: one with non-shifted but cropped images and one with shifted and cropped images. Both reconstructed voxel models underwent the same procedure for edge determination, and the surfaces where best fitted onto each other. For the edge determining and best fitting of the 2 voxel models the Volume Graphics® software was used. The comparison of the two reconstructions is shown in Figure 12 by means of a colour plot. Figure 13 shows the histogram of the deviation between the two reconstructions. The deviation between the surfaces varies between a minimum of -10 µm and a maximum of +11 µm and has a standard deviation of less than 5 µm, which is about one sixth of the voxel resolution of 33 µm.

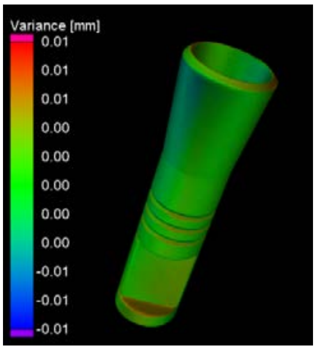

Figure 12 Comparison of the reconstruction with and without drift compensation

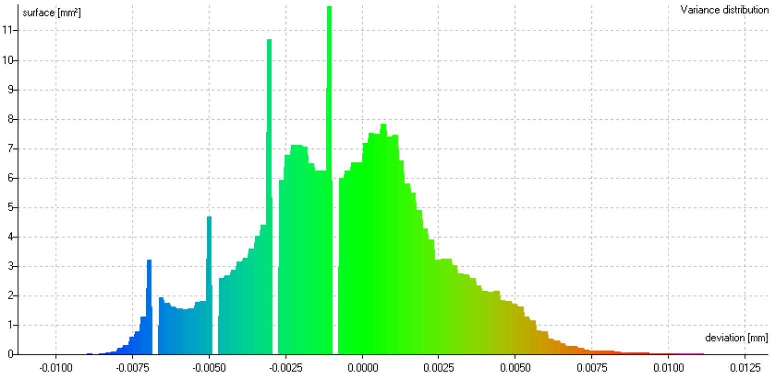

Figure 13 Histogram of the deviation between the two reconstructions; with and without drift compensation

Future Improvements

For future improvements it would be better to use a set of 3D calibrated points similar to the spheres used on the industrial case. Making use of such a calibration artefact during the scanning would make it possible to determine the exact position of the spot towards the detector. This information could then be linked to the reconstruction software, avoiding positional shifts in the 2 images to interfere with the reconstruction.

Conclusions

This paper describes a method for determining the positional stability of 2D X-ray images used for CT purposes. By measuring stationary positions during a scan it is easy to determine the magnitude of the positional drift of 2D X-ray images. On the tested CT machine a vertical shift (y- direction) was observed. This shift could be explained by the combination of mounting of the X-ray tube inside the XCT machine and the heating of the tube during the scanning process. A few suggestions are made to improve the 2D positional stability, and one of these methods is implemented on an industrial case. During a scan of an object steady positions are measured during the rotation of the object. The shift of the steady positions can be used to compensate for positional drift of the images. In the industrial case study, both the original images and the compensated images are reconstructed and these reconstructed models are compared with each other. This proves that there is an easy way to quantify and even to compensate for positional instability of 2D X-ray images used for CT.

Acknowledgements

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