Optimization Of Scan Range For 3d Point Localization In Statscan Digital Medical Radiology

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Abstract: The emergence of computerized medical imaging in early 1970s, which merged with digital technology in the 1980s, was celebrated as a major breakthrough in three-dimensional (3D) medicine. However, a recent South African innovation, the high speed scanning Lodox Statscan Critical Digital Radiology modality, posed challenges in X-ray photogrammetry due to the system's intricate imaging geometry. The study explored the suitability of the Direct Linear Transformation as a method for the determination of 3D coordinates of targeted points from multiple images acquired with the Statscan X-ray system and optimization of the scan range. This investigation was carried out as a first step towards the development of a method to determine the accurate positions of points on or inside the human body. The major causes of errors in three-dimensional point localization using Statscan images were firstly, the X-ray beam divergence and secondly, the position of the point targets above the X-ray platform. The experiments carried out with two reference frames showed that point positions could be established with RMS values in the mm range in the middle axis of the X-ray patient platform. This range of acceptable mm accuracies extends about 15 to 20 cm sideways towards the edge of the X-ray table and to about 20 cm above the table surface. Beyond this range, accuracy deteriorated significantly reaching RMS values of 30mm to 40 mm. The experiments further showed that the inclusion of control points close to the table edges and more than 20 cm above the table resulted in lower accuracies for the L - parameters of the DLT solution than those derived from points close to the center axis only. As the accuracy of the L - parameters propagates into accuracy of the final coordinates of newly determined points, it is essential to restrict the space of the control points to the above described limits. If one adopts the usual approach of surrounding the object by known control points, then the limited space with an acceptable accuracy potential for the L - terms would not be large enough to enclose an adult human body surrounded by suitably positioned control points. This shortcoming can be overcome by making use of two further observations made in the course of this investigation. These observations were firstly, that the best image orientation angles are 0^0 and 40^0 to 60^0, and secondly, that no significant improvement could be achieved when using more than two images. This observation contradicts the theory of adjustment and observations, and can be investigated in further research. The possible observation method deduced from this is as follows: First, a frame with well distributed control points with accurate 3D coordinates and of approximately the size of a human body is placed on the X-ray table and imaged with the X-ray beam in the 0 degree position. This makes it possible to determine L - parameters for this ray orientation; 2. The frame is removed; the patient is positioned in the control space; and an X-ray image of the patient is taken 3. The X-ray source is rotated to a new position between 40^0 and 60^0 and a second image of the patient is acquired and fourth, the patient is removed and replaced by the frame. A final image of the frame is now acquired. Steps 1 and 4 serve to determine the L-parameters for the two X-ray source positions, while steps 2 and 3 provide the image coordinates of the required object points on or inside the patient's body. This approach can only then result in accurate point positions, if the patient remains motionless for the duration of steps 2 and 3. An alternative to this observation design would be simultaneous imaging from two X-ray sources, one with 0^0 orientations and the other with an orientation between 40^0 and 60^0.

Key Words: Optimization, Lodox Statscan, Radiology, Modality, Localization, DLT.

INTRODUCTION

1.1 The Lodox Statscan System

Statscan Critical Digital Radiology (DR) is a flexible format digital imaging system, which is based on linear slit/slot scanning technology that uses a linearly moving focal spot origin (see http://www.lodox.com). High quality digital outputs of radiographic images are acquired from the system. Stascan digital technology was developed in 2003 by Lodox (Pty) Ltd., and can be traced back to the South African mining industry. The forerunner of Stascan was a digital X-ray security system (Scannex) owned by De Beer' diamond mines. Mine workers were scanned randomly as they exited the mines to prevent in-the cavities gems theft. Scanning was in standing mode (see figure 1(a)), where workers had to pass through the X-ray system and were exposed to radiation. A significant design modification of the security system to be used in medical radiology is the introduction of a patient platform as shown in figure 1 below.

***Figure 1**: De Beers Scannex (a) and Lodox Statscan System*

The experimental procedures explored the suitability of the Direct Linear Transformation (DLT) as a method for the determination of 3D coordinates of targeted points from multiple images acquired with the Statscan X-ray system. This investigation was carried out as a first step towards the development of a method to determine the accurate positions of points on or inside the human body. The experiments carried out with two reference frames showed that point positions could be established with RMS values in the mm range in the middle axis of the X-ray patient platform. This range of acceptable mm accuracies extends about 15 to 20 cm sideways towards the edge of the table and to about 20 cm above the table surface. Beyond this range, accuracy deteriorated significantly reaching RMS values of 30 to 40 mm. The experiments further showed that the inclusion of control points close to the table edges and more than 20 cm above the table resulted in lower accuracies for the L - parameters of the DLT solution than those derived from points close to the center axis only. As the accuracy of the L - parameters propagates into accuracy of the final coordinates of newly determined points, it is essential to restrict the space of the control points to the above described limits.

1.2 Research Objective

The aim of this research is to generate a method for reconstructing the third-dimension from two-dimensional (2D) X-ray images acquired using Stascan Digital Radiology system. Precision and accuracy in three-dimensional (3D) localization of points of interest on static models made of 3D metal frames will be investigated.

1.3 Research Problem Justification Statement

Statscan digital X-ray output is usually in the form of two-dimensional images. The system can produce a full body radiograph with extremely low X-ray dosage as compared to Computed Tomography (CT) systems. However, without the capability of 3D imaging, the Statscan cannot be used as an alternative to CT systems in applications that require 3D diagnosis. A technique for localization of points of interest in three-dimensional space will be investigated to establish if Statscan can appropriately be used in clinical applications that do not require the 3D volume. The scanning speed and quality radiography of the Statscan has greatly revolutionized digital radiology, but the 2D output still remains an inferior representation of human anatomy. As stated above, the Statscan imaging technology is cost – effective and exposes the patient to less X-ray dosage than other methods like CT-scanning. Thus an extension of the Statscan output to 3D-data will be highly desirable.

1. METHODOLOGY

2.1 Experimental Procedure

The first step was the design of two 3D metal frames of different sizes with reflective targets. The targets were clearly visible on the photographed images. Since the same 3D metal frames were scanned using the Statscan system, the targets were made of material of different density from the joining metal bars. The use of high-resolution digital cameras in conjunction with retro-reflective targets has enabled highly-automated, high-precision close-range photogrammetric measurements. The term close-range photogrammetry has been used for photogrammetric procedures that are performed using images taken when the object-to-camera distance is generally less than 100m (Marzan and Karara (1976)). The use of static metal frames on the Statscan machine was aimed at testing the performance of the system in terms of accuracy in 3D reconstruction using images taken from different orientations. A static frame model was used instead of imaging a human body to eliminate the additional distortions caused by involuntary body movements. Again, the measurement of soft tissue and bones was not done due to lack of distinct marks on the internal structures of the human body. The two different metal frames are shown in figure 2.

***Figure 2**: Metal frame models of different sizes.*

Each metal frame comprised of two sets of points; the control points and the test points that were reconstructed from the Statscan images. Six visible targets at the extremes of the frames were chosen as control, while the rest of the points formed the test points. Digital photogrammetry method was used to provide the space positions for both the control points and the test points. The basis of modern digital photogrammetric metrology is the CCD cameras, whose use has permitted the acquisition of images of very large dynamics. The term 'photogrammetric metrology' covers the whole range of metrology activities that exploit photogrammetric processes based on image acquisition and image processing, that historically hardly ever took place in real time (Kasser and Egels, 2002). A digital image can be defined as a regular array of pixels, or picture elements, and it can be described in terms of geometry and radiometry (Mikhail et al., 2001). Initially, the space positions for the test points were taken as unknown, and to be determined from Statscan images. The results obtained from 3D reconstruction using Statscan images were compared to the space positions of test points to establish point reconstruction accuracy. In order to provide an independent check for the control and test data, precise theodolite positioning method was used to acquire a separate three-dimensional data set. The two data sets were compared by means of a three-dimensional similarity transformation of the digital photogrammetric coordinates into the positions derived by theodolite measurements. The rigid body transformation uses a mathematical model that preserves the relative space positions of the points being transformed (Rüther, 2005; APG313S). Prior to the transformation of the coordinates from one system to the other, the object and target systems should both be in either right-hand or left-hand coordinate system. After computation and confirmation of agreement between the two methods using Australis Photogrammetric software (Fraser, 2001), one set of space control was used in X-ray 3D reconstruction. The Root Mean Square (RMS) of the XYZ residuals obtained from the transformed coordinates was 0.5 mm. The deduction from these results was that the digital photogrammetric procedure was satisfactorily accurate in determination of space control points that could be used in 3D localization for the Statscan digital X-ray system.

2.2 Three-Dimensional Reconstruction Using Statscan Images

The frame images scanned with the Statscan system were used to obtain a solution for the 3D localization of the visible distinct targets on each metal frame. In every experiment, at least two images were combined at a time to solve for the point positions in 3D space. The first image taken at frontal position was used with every other subsequent image, thus the angle between the images increased progressively. The experiments tested the change in positioning accuracy with increase in convergence angle. A total of twenty two target points on the small frame were reconstructed from scanned images. Most of the targets on the big metal frame were not visible due to the limitation in imaging geometry of the scanner. Out of the seventy six targets on the big metal frame, only twenty three could be measured, and even less in some images. The root mean square errors in localization derived by comparison with the control frame were computed and plotted in graphs for visualization. Table 1 gives all the images used in the different experiments. The metal frames were scanned by manually selecting the scan angle that rotated the X-ray tube along the Statscan's C-arm.

Table 1

Metal frame images used in Statscan 3D point localization

Object	Images scanned with Statscan (degrees)
Big metal frame	5^0, 9^0, 14^0, 18^0, 22^0, 26^0, 30^0, 34^0, 39^0, 43^0, 45^0, 49^0, 53^0
Small metal frame	Set 1: 0^0, 5^0, 9^0, 14^0, 18^0, 22^0, 26^0, 30^0, 34^0, 39^0, 43^0, 45^0, 49^0, 53^0 Set 2: 0^0, 4^0, 10^0, 15^0, 20^0, 24^0, 30^0, 34^0, 40^0, 45^0, 50^0, 55^0, 60^0, 65^0, 69^0, 74^0, 84^0, 90^0

The targets on the big frame images obtained at scan angles beyond 53 degrees could not be measured hence images were not used. Figure 3 shows a sketch of the Statscan's C-arm and some X-ray scan orientations.

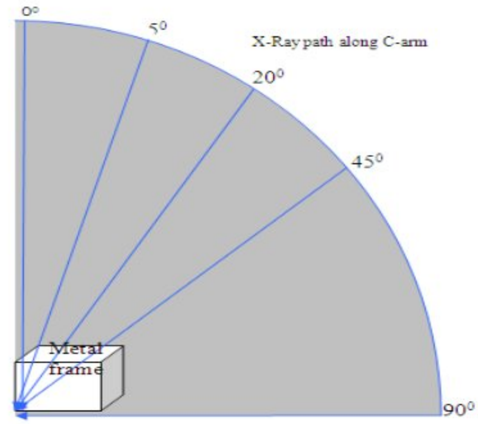


Figure 3 *Schematic of different X-ray scan orientation angles along the Statscan's C-arm (not scaled).*

The Lodox Statscan object space coordinates were computed through a transformation from 2D X-ray image coordinates into 3D control object space coordinates. The control and test space coordinates obtained from digital photogrammetry were used in Direct Linear Transformation (DLT). The measured image coordinates were exported into Direct Linear Transformation (DLT) code for three-dimensional point reconstruction. The DLT method was adopted as originally proposed by Abdel-Aziz and Karara in 1971, (see Karara, 1989). Six control points are identified distributed on the corners and inside the metal frame. The precision of the DLT terms, which is an internal measure of accuracy, was obtained by computing the variance-covariance matrix of the determined DLT parameters. In order to check the external accuracy in 3D localization, the space coordinates were compared to those obtained by digital photogrammetry. Accuracy, the measure of agreement between the observed and photogrammetric X, Y and Z coordinates was computed. The least squares solution was executed iteratively to compute the values image coordinates x and y into the object coordinates X, Y and Z can be written as shown in equation 1. for the DLT parameters; (L_1) through (L_{11}). The standard DLT equations used for transforming image coordinates x and y into the object coordinates X, Y and Z can be written as shown in equation 1.

$$\left. \begin{aligned} x & \quad \frac{L_1 X + L_2 Y + L_3 Z + L_4}{L_9 X + L_{10} Y + L_{11} Z + 1} \\ y & \quad \frac{L_5 X + L_6 Y + L_7 Z + L_8}{L_9 X + L_{10} Y + L_{11} Z + 1} \end{aligned} \right\} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

Where;

$L_1 - L_{11}$ are the transformation parameters,

x, y are the image coordinates,

X, Y, Z are the control coordinates.

The point localization error (D) was computed by taking difference between photogrammetry derived coordinates (X_P, Y_P, Z_P) and computed DLT coordinates (X_C, Y_C, Z_C). Thus the RMS (XYZ) was obtained as shown in equation 2.

$$RMS(XYZ) \quad \sqrt{\frac{\sum\left(DX^2 + DY^2 + DZ^2\right)}{3n}} \quad \ldots\ldots\ldots(2)$$

Where; DX, DY and DZ are residuals in X, Y and Z respectively; n is the total number of target points.

3. RESULTS

3.1 Reconstruction of the Big Reference Frame Results

The experiments were designed to study the change in attainable point positioning accuracy with progressive image convergence angles. The first image was taken at 5 degrees, and this image was combined with each other image taken after moving the X-ray tube. Image coordinates for all the scans were measured. Two images were used at a time in the DLT algorithm and point positioning accuracy was computed for each case. Six points (2, 4, 67, 72, 74 and 81) at the extremes and inside of the metal frame were chosen as control. The dimensions of the big metal frame used are 900mm*600mm*205mm. Figure 4 shows the measured targets on 14 degree Statscan image.

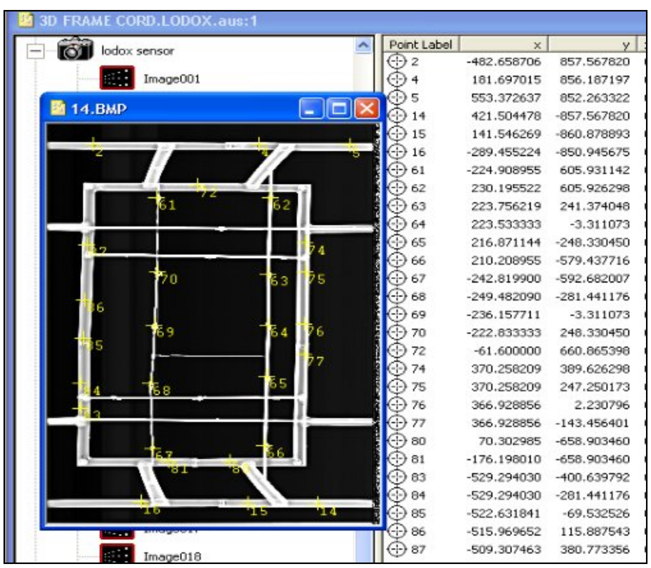


Figure 4 *Measured target points of Statscan 14 degree image for the big metal frame.*

The presented results showed gradual changes in 3D localization accuracy obtained using images scanned between 5 and 53 degrees orientation. Target points at the edge of the frame appeared to be more displaced as compared to those imaged at the center mid-position of the frame (see figure 1-8). The changes were irregular and showed no significant trend. Further experiments were conducted using images of the small metal frame taken along the whole scan range of the Statscan C-arm. Figure 5 is a graphical representation of positioning accuracy for the big frame from two image DLT solutions.

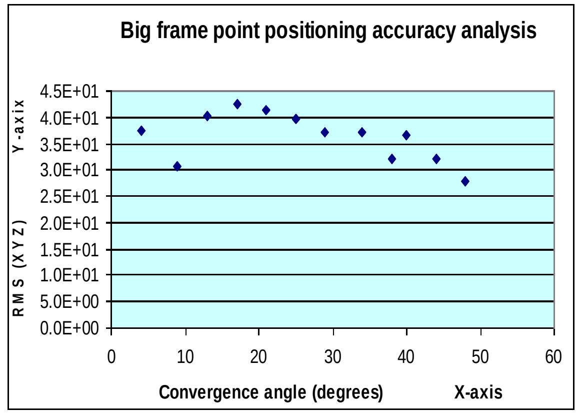


Figure 5 *Plot of Statscan big frame image orientations against point positioning accuracy RMS (XYZ).*

The results obtained from 5 degree and 53 degree image combination were used to plot the reconstructed points in 3D space. Matlab software was used to display the 3D graphic of the points. The points in red are the photogrammetry control points while the black points are the reconstructed points. Points within the inside of the metal frame were found to be reconstructed at a higher accuracy as compared to those at the edges of the frame. An explanation for the disparity is due to the X-ray beam divergence. Figure 6 shows all the correspondence of the determined points to the control points.

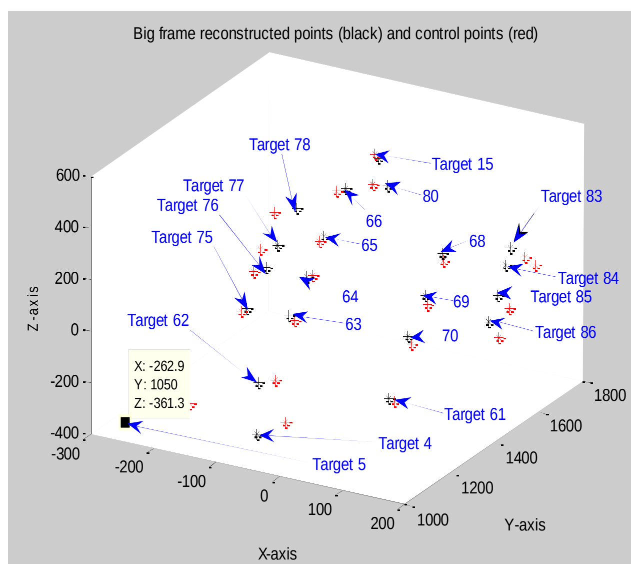


Figure 6 *3D graphic of the Statscan big frame reconstructed points (black) and control points (red) using 5 degree and 53 degree image combinations.*

3.3 Effect of X-ray Beam Divergence on Point Positioning Accuracy

The big frame occupied the whole scan space on the Statscan X-ray platform. The targets on the frame edges were imaged at the outward side of the X-ray beam which diverges from the centre. These edge points were 4, 5, 75, 76, 77, 78, 80, 83, 84, 85 and 86. The points in the middle of the frame (61, 62, 63, 64, 65, 66, 68, 69, 70), were imaged at the near parallel central X-ray beam. Positioning accuracy of the edge points was lower than that of the mid points. Therefore, the overall accuracy for all the points on the big frame was affected by the X-ray beam divergence. The results are represented graphically in figure 7.

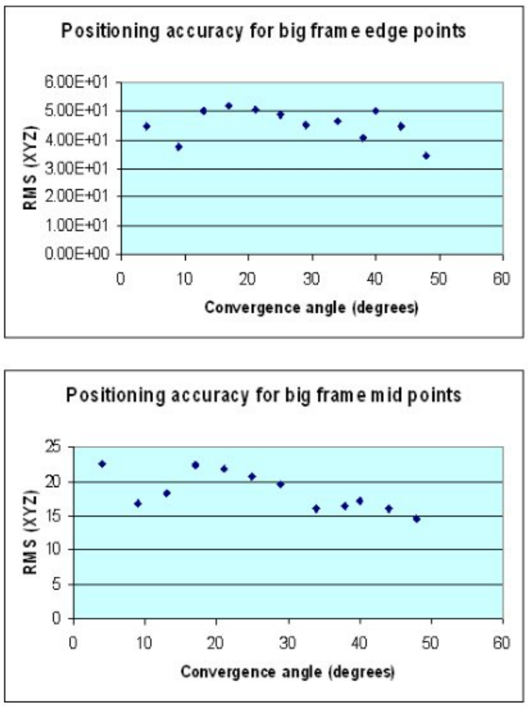


Figure 7 *Big frame positioning accuracy for edge points (a) and mid points (b)*

3.2 Reconstruction of the Small Reference FRAME Results

Image coordinates of all the target points on the small frame were measured from all the images recorded between 0 degrees and 45 degrees range in the Statscan C-arm rotation. Six control points were used in the DLT solution and were chosen from the corners (see figure 9(a)). The minimum number of six was found to be sufficient after testing with a number of experimental cases. The 3D point reconstruction process was achieved through combining each successive image with the image taken at 0 degree position. This procedure was aimed at investigating the change in point localization accuracy with increase in convergence angle. The results showed that the coordinates of points lying on the surface of the X-ray table were closer to those of the control points than the ones at the top of the frame. The dimensions of the small metal frame are 350mm*310mm*265mm. Figure 8 shows labeled point targets on the small frame Statscan image scanned at 10 degrees orientation. The bones inside the frame provide orientation for the images.

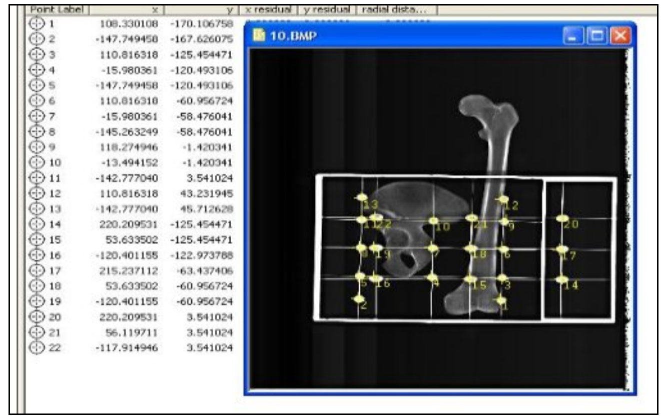


Figure 8 *Labeled target points for Statscan small metal frame image taken at 10 degrees.*

The reconstruction accuracy of the small metal frame was better than that of the big frame. The explanation for the difference in positioning accuracy of the two frames is due to their different sizes. The small frame was imaged at the central part of the X-ray beam with less divergence. This was unlike the case in the big frame because the whole beam was used to cover the frame which occupied the whole width of the scanning platform. Figure 9(a) shows all the point targets in 3D space together with the arrangement of chosen control points used in the DLT solution. The point positions of reconstructed points using 0 & 45 degree image combination and the photogrammetric control coordinates has been shown by plotting the reconstructed points in black and the space control values in red. Point nine and twelve that are at the bottom of the frame, lying on the platform have been found to merge as one point due to high positioning accuracy as shown in the display in figure 9(b).

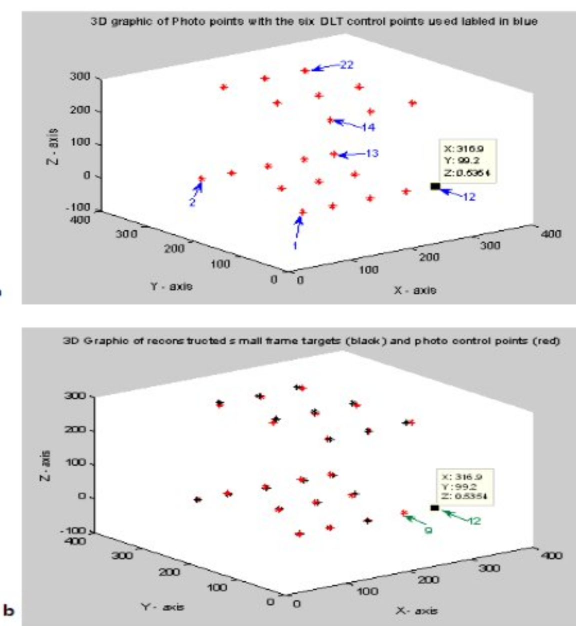
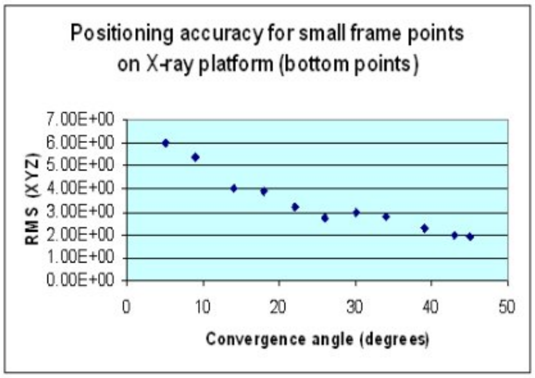


Figure 9 *Labeled control points used in Statscan small frame reconstructed (a), and both control frame points (red) plotted together with respective reconstructed points (black) (b).*

The first image taken at 0 degrees was combined with the rest of the images in the DLT solution. This progressive increase of convergence angle resulted in an inverse proportionality between the intersection angle and computed RMS (XYZ). The points lying on the X-ray platform (1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12 and 13) have been localized at 1.9mm root mean square error (RMS) in XYZ. Those points positioned above the X-ray platform, (14, 15, 16, 17, 18, 19, 20, 21, 22) have been localized at RMS (XYZ) of 4.3mm. The accuracy in positioning the top plane and bottom plane of the small frame for all the experiments with 0 to 45 degrees images are shown in Figure 10 (a) and (b) for each case. Reconstruction of the points lying on the bottom plane using similar image combinations was higher than those on the top plane.

a



b

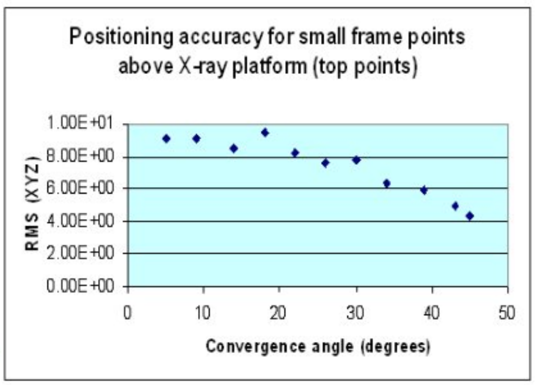


Figure 10 *Positioning accuracy for small frame bottom (a) and top (b) points on the Statscan X-ray platform.*

3.4 Optimal Scan Range for the Statscan System

Images of the small metal frame were recorded at an interval of near 5 degrees within the full machine range (0 – 90 degrees). The system performance seemed to fluctuate within close similar convergence angles as shown in images taken between 0 – 45 degrees, and when scans were repeated for 0 – 90 degrees range. The range between 45 degrees and 60 degrees showed the highest accuracy in point reconstruction. This range can be taken as the Statscan optimal scanning range for acquiring images to be used in 3D reconstruction. Beyond 60 degrees, the accuracy decreases with irregular trend. Figure 11 visualizes the positioning accuracy changes in each successive reconstruction. In order to show the trend, second order polynomial curve fitting has been done.

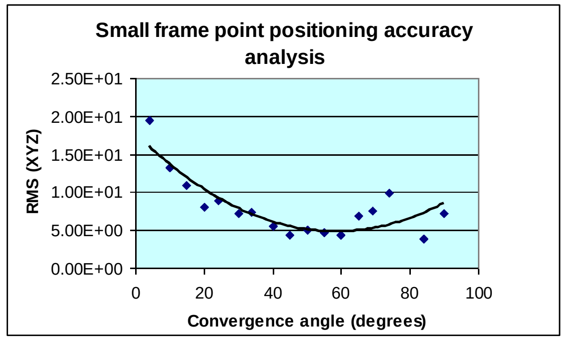


Figure 11 *Positioning accuracy RMS (XYZ) against convergence angle for Statscan small frame (0 – 90 degree images).*

4. CONCLUSION AND RECOMMENDATIONS

Localization accuracy of points of interest in 3D space on the Statscan system is affected by object position on the X-ray table. The major causes of errors in three-dimensional point localization using Statscan images were firstly, the X-ray beam divergence and secondly, the position of the point targets above the X-ray platform. The experiments carried out with two reference frames showed that point positions could be established with RMS values in the mm range in the middle axis of the X-ray patient platform. This range of acceptable mm accuracies extends about 15 to 20 cm sideways towards the edge of the X-ray table and to about 20 cm above the table surface. Beyond this range, accuracy deteriorated significantly reaching RMS values of 30mm to 40 mm. The experiments further showed that the inclusion of control points close to the table edges and more than 20 cm above the table resulted in lower accuracies for the L - parameters of the DLT solution than those derived from points close to the center axis only. As the accuracy of the L - parameters propagates into accuracy of the final coordinates of newly determined points, it is essential to restrict the space of the control points to the above described limits. If one adopts the usual approach of surrounding the object by known control points, then the limited space with an acceptable accuracy potential for the L - terms would not be large enough to enclose an adult human body surrounded by suitably positioned control points. This shortcoming can be overcome by making use of two further observations made in the course of this investigation. The best image orientation angles that can be used for 3D localization are 0^0 combined with 40^0 to 60^0 image orientation angles. The results indicated no significant improvement could be achieved when using more than two image combinations at a time. The possible patient observation procedure deduced from the above experiments is as follows:-

1. A frame with well distributed control points with accurate 3D coordinates and of approximately the size of a human body is placed on the X-ray table and imaged with the X-ray beam in the 0 degree position. This makes it possible to determine L parameters for this ray orientation.
2. The frame is removed; the patient is positioned in the control space. And an X-ray image of the patient is taken.

3. The X-ray source is rotated to a new position between 40^0 and 60^0 and a second image of the patient is acquired.
4. The patient is removed and replaced by the frame. A final image of the frame is now acquired.

Steps 1 and 4 serve to determine the L-parameters for the two X-ray source positions, while steps 2 and 3 provide the image coordinates of the required object points on or inside the patient's body. This approach can only then result in accurate point positions, if the patient remains motionless for the duration of steps 2 and 3. An alternative to this observation design would be simultaneous imaging from two X-ray sources, one with 0^0 orientations and the other with an orientation between 40^0 and 60^0.

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