Tuning of X-Ray Parameters for Noise Reduction of an Image-Based Focus Position Measurement of a C-Arm X-Ray System*

Sabine Thürauf[1], Florian Vogt[2], Oliver Hornung[2], Mario Körner[2], M. Ali Nasseri[3] and Alois Knoll[4]

***Abstract*— In surgery or interventional radiology 2D/3D overlays of X-rays combined with previously recorded 3D volumes support the physician with additional visual information. Typical X-ray systems in these fields are C-arm systems. First of all, the 3D volume and the 2D images need to be registered. Afterwards, if the system moves, errors between the real world pose and the nominal pose of the system appear. One possible way to overcome this problem is an absolute calibration of the system. With this approach the projection geometry can be defined accurately enough for a whole working volume. Therefore, measurements of the end effector pose serve as input. A potential method to determine the pose of the C-arm, is a pose estimation by X-ray observations of a calibration phantom. This work evaluates how the focal spot size, the pixel size and the dose affect the noise at the pose estimation of the C-arm by X-ray observations.**

I. INTRODUCTION

Augmented reality entered the OR (operation room) several years ago. X-ray images with overlaid extra information are already used in surgery. Often 3D volumes of the VOI (volume of interest) are recorded for diagnostical purposes or to plan an intervention. These volumes, together with the planning information can be overlaid to images, which are generated during an intervention (see Fig. 1).

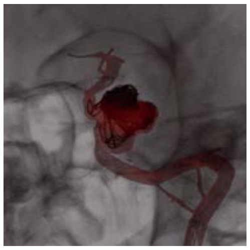

Fig. 1: Overlay of a CBCT (cone beam computed tomography) and an X-ray of an aneurysm [1]

To achieve these overlays a registration of the 3D volume and the X-ray system needs to be executed, such that the system's projections geometry is known relative to the volume. After an initial registration is performed, it is possible to use the overlays. However, if the system moves and its calculated pose information does not match to its real pose, deviations become visible in the overlay. To overcome these geometric errors a calibration of the C-arm system is performed.

Different data-based methods were applied until now [2]. In contrast to all these methods, which directly use the estimated projection parameters of a system pose to compensate the errors, we plan to use a model-based method, which involves an absolute robot calibration to estimate the absolute system pose. Afterwards, the real world pose of the system is known accurately in a whole working volume and not only at some calibrated poses.

Common measurement systems for robot calibration are different tracking devices (e.g. laser trackers), CMMs (coordinate measurement machines) and camera systems [3]. However, we estimate the pose of the system with X-ray projections of a calibration phantom for the absolute robot calibration of the C-arm system. Therefore, sensor noise plays an important role for the accuracy. This work evaluates different factors, which influence the effect of noise on the pose estimation of a C-arm system based on X-ray observations.

II. PINHOLE CAMERA MODEL

C-arm X-ray systems with flat panel detectors do not include lens systems. Because of that, a distortion-free pinhole camera model is sufficient to model the projection geometry. As shown in Fig. 2 the X-ray tube includes the focal spot (3D position) and the detector defines the image plane (3D position and 3D orientation).

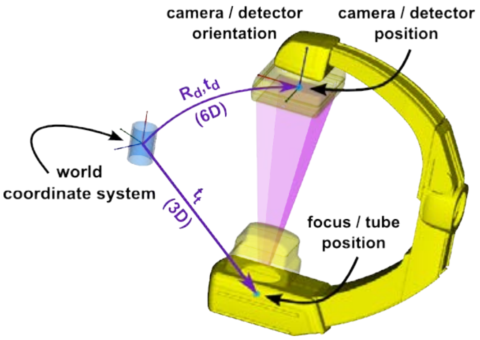

Fig. 2: 9D projection geometry of a C-arm

The projection model is described by the following equation

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[1] Sabine Thürauf is with fortiss GmbH, An-Institut Technische Universität München, Germany, Guerickestr. 25, 80805 München, Germany `thuerauf@fortiss.org`

[2] Florian Vogt, Oliver Hornung and Mario Körner are with Siemens Healthcare GmbH, Siemenstr. 1, 91301 Forchheim, Germany `oliver.oh.hornung, mario.koerner, florian.vogt@siemens.com`

[3] M. Ali Nasseri is with Augenklinik Rechts der Isar, Technische Universität München, Ismaninger Str. 22, 81675 München, Germany `ali.nasseri@mri.tum.de`

[4] Alois Knoll is with Department of Robotics and Embedded Systems, Institut für Informatik, Technische Universität München, Boltzmannstr. 3, 85748 Garching, Germany `knoll@in.tum.de`

for the 3×4 projection matrix P:

$$P = \begin{bmatrix} \frac{SID}{p_x} & 0 & \frac{pp_x}{p_x} & 0 \\ 0 & \frac{SID}{p_y} & \frac{pp_y}{p_y} & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \cdot \begin{bmatrix} \mathbf{R} & 0 \\ 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} I_{3\times 3} & -\mathbf{t} \\ 0 & 1 \end{bmatrix} \quad (1)$$

The intrinsic camera parameters are the SID (source to image distance), the pixel sizes in x- and y-direction p_x and p_y, and the coordinates of the principal point pp_x and pp_y. The extrinsic parameters are the rotation $\mathbf{R} \in \mathbb{R}^{3\times 3}$ the translation and $\mathbf{t} \in \mathbb{R}^{3\times 1}$ from the world frame to the camera frame.

Images of a helical calibration phantom are utilized to estimate the parameters of the camera model with an optimizer. The x- and y-axis of the camera coordinate system are parallel to the detector plane. The z-axis completes the right-hand coordinate system and points in beam direction of the X-ray system.

III. POSE MEASUREMENT ACCURACY FOR ABSOLUTE CALIBRATION

For 2D/3D registration, registration accuracies of e.g. $0.5 - 4.8mm$ are needed [4]. This accuracy depends on the application and the spacial resolution of the devices used [5]. For the absolute calibration we try to reach the lower bound of the registration accuracies, which means: max. $0.5mm$ displacement in the volume. To achieve this, commonly the measurement system, which serves as the input for the calibration, needs to be at least as accurate as the goal accuracy. However, accuracy requirements for the measurement system can be approximated by typical accuracy ratios, which are e. g. 4:1 and 10:1 [6]. For an overlay, which needs an accuracy of $0.5mm$ combined with an accuracy ratio of 10:1, the maximal allowed measurement error of the detector position in x- and y-direction (in camera coordinate system) is $50\mu m$, if exclusively an in-plane displacement of the detector appears at the measurements.

IV. FOCUS POSITION

During the iterative estimation of P errors of one of the 9 parameters lead to inaccuracies of the other parameters. Therefore, we choose to evaluate only the focus position. This parameter is defined directly by the extrinsic parameter $\mathbf{t}$, such that no further computation errors appear at the calculation. Furthermore, at least one coordinate of the focus position needs to be known for the absolute calibration, because the tube has its own kinematic chain, for which the end effector is defined exclusively by the focus position. Cho et al. already showed that the z-coordinate (in camera coordinate system) is 10 times more sensitive to imaging inaccuracies than the x- and the y-coordinate [7]. Because of that, we suspect, that the noise of the z-coordinate is higher than for the other coordinates of the focus. In addition, we expect that the noise is smaller for smaller pixel sizes and smaller focal spot sizes. Furthermore, another presumption is, that an increase of the dose leads to a decrease of noise.

V. EXPERIMENTAL SETUP

The 9D pose of the system is measured with X-ray images of a helical calibration phantom, which is placed at the OR table (see Fig. 4). The phantom and the system are positioned, such that the phantom is fully visible on the X-ray projection (see Fig. 3).

Neither the C-arm nor the phantom are moved during the experiments. For all experiments a frame rate of $7.5\, frames\ per\ seconds$ is chosen together with a time interval of $20s$, yielding a series of 151 images for each run. The dose (amount of X-ray energy absorbed per mass) is varied from $0.080\mu Gy$ to $5.4\mu Gy$, the focal spot size are $0.3mm$, $0.4mm$ or $0.7mm$ and the pixel size is $p_x = p_y = 154\mu m$ or $308\mu m$. The standard deviation of the focus position is computed for each run.

VI. RESULTS

Table I shows the minimal and maximal standard deviations of the focus position for x-, y- and z-coordinate in camera coordinate system.

TABLE I: Minimal and maximal standard deviations of the focus coordinates in camera coordinate system

	x-coord.	y-coord.	z-coord.
min. standard deviation	$0.007mm$	$0.005mm$	$0.066mm$
max. standard deviation	$0.025mm$	$0.017mm$	$0.301mm$

For all experiments the z-coordinate of the focus position was determined about 10 times less accurate than the x- and y-coordinate and x- and y-coordinate were in nearly the same range.

Fig. 5 shows the x- and y-coordinate for the two different pixel sizes and the complete range of dose values. In general, the standard deviation decreased, if the dose increased. Furthermore, the standard deviation is smaller for smaller pixel size. The same behaviour was observed for the z-coordinate as well.

In Fig. 6 the standard deviation of y-coordinate of the focus point is displayed for different focal spot sizes. The standard deviation is decreased, in case that the focal spot size is decreased. Similar behaviours are observed for the x- and z-coordinate

Fig. 3: Example X-ray image of the helical calibration phantom

Fig. 4: Experimental set up with C-arm system and calibration phantom

VII. DISCUSSION

Cho et al. proofed that the focus coordinate in beam direction (z-direction) is estimated less accurately than the others [7]. The results of Table I show that, as expected, the z-value of the focus position is about 10 times more sensitive to image errors than x- and y-coordinate.

Further dependencies were observed, too. In the plot of Fig. 5, the standard deviation for the smaller pixel size is lower. An explanation therefore is, that the smaller the pixel size is, the more accurate the spherical markers of the phantom can be detected in the image. This is the case, because the increased spacial information improves the detection of the circles in the image. Finally, the increased amount of spacial information of the phantom leads to a more accurate estimation of the C-arm pose relative to the phantom.

Furthermore, Fig. 5 shows that the standard deviation decreases, if the dose value increases. The relative influences of scatter, quantum noise, and further pixel noise onto the image decreases for an increased dose value. Hence, the SNR (signal to noise ratio) is higher for higher dose values [8]. This means, that the information content of an image is increased, such that relatively more information about the marker positions is given. With this increased image information, the markers are detected more accurately, which results in a more accurate estimation of the system pose.

Also, the focal spot size influences the pose estimation. Smaller focal spots lead to smaller noise of the focus position. An explanation for that is, that the smaller the focal spot is, the sharper the image is. So, the marker edges are displayed sharper and a more accurate detection is possible. Consequently, this leads to an improved estimation of the C-arm pose.

VIII. CONCLUSIONS

For a C-arm pose measurement system for an absolute calibration high accuracies ($\leq 50\mu m$) are needed. Therefore, it is important to know how sensor noise can be decreased. Furthermore, it needs to be checked how accurate the absolute C-arm pose is measured. In our case, the pose measurement is performed by X-ray observations of a calibration phantom. This work showed that for a minimal pixel size, a maximal dose value, and a minimal focal spot size the noise of the measured focus position is minimal. However, the noise in beam direction (min. $66\mu m$) is about 10 times higher than in the other coordinate values (min. $7\mu m$ or $5\mu m$), which underlines the prediction, that the z-coordinate is 10 times more sensitive than the other two coordinates. Because of that, the other parameters should gain more influence for the later absolute calibration of the system, to overcome inaccuracies induced by sensor noise.

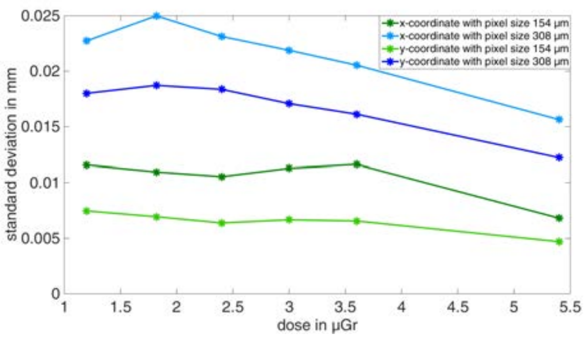

Fig. 5: Standard deviation of the focus position in x- and y-coordinate with respect to the dose with a focus spot size of $0.3mm$

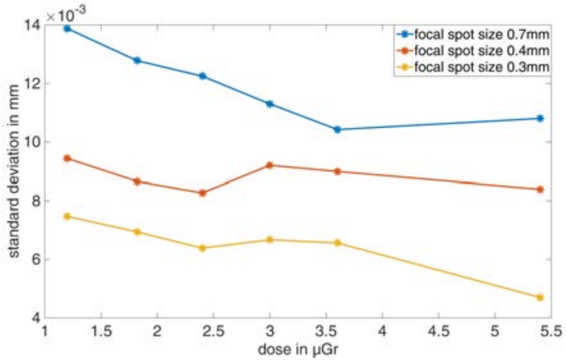

Fig. 6: Standard deviation of the focus position in y-direction with respect to the dose with a pixel size of $154\mu m$

These experiments showed that the noise with tuned parameters is in a scale, which is sufficiently small ($5\mu m$ or $7\mu m \leq 50\mu m$), such that this measurement technique can potentially be used as measurement method for the absolute calibration of a C-arm system.

In further experiments the absolute accuracy of the absolute 9D pose of the C-arm with the measurement technique described in this paper needs to be evaluated. With this additional work, it is checked, if an absolute pose measurement of C-arm systems based on X-ray observations of a calibration phantom is a possible measurement method for the input of an absolute calibration of a C-arm system.

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