Measurement of cardiovascular structures in angiographic images with navigated imaging

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Abstract. In this paper a system is presented to measure cardiovascular structures in angiographic images. The main benefit is the metric measurement instead of relative sizes as used today. Currently measurements are carried out as relative estimations under radioscopic monitoring. This means a high x-ray radiation to patient and medical staff. Unnecessary radiation will be avoided if it is possible to measure lengths of cardiovascular structures in 2D images. This approach is realized by the combination of a position measuring device with an angiographic system.

1 Introduction

Cardiology is a division of internal or pediatric medicine and focuses the diagnosis and treatment of the heart and cardiovascular system. Angiography as one method of cardiology is a technique to determine e.g. stenosis with radioscopic images after injection of a contrast agent (dye, usually iodine or barium) to increase the contrast of vessels and cardiovascular structures. With help of Seldinger technique a thin catheter is introduced in a great vessel and guided under radioscopic monitoring to the region of interest. The dilatations of stenosis are carried out with balloon catheters by inflating the balloon. The widened stenosis is stabilized with a vessel stent.

To produce radioscopic images of cardiovascular structure special equipment is needed the so-called c-arm. A c-arm is a mechanical structure that positions an x-ray source and an x-ray image intensifier (XRII). An angiographic system consists of one or two c-arms (monoplane/biplane). A biplane angiographic system is needed for the concurrent imaging of cardiovascular structure for two perspectives. This is necessary due to pulsation and respiration of the patient. The temporal and spatial distributions are the main interferences of radioscopic imaging.

Main drawbacks of state of the art treatment are high x-ray radiation to patient and medical staff, limited measurement capabilities, and limited 3-dimensional visualization [1][2].

In this work a prototype for the navigated imaging (current implementations for CT [3] and surgical c-arm systems [4]), that means the combination of navigation with imaging systems, is presented, which gets over limitations of current measurement and built up the basis for future development of exact volume reconstruction.

2 Material and Methods

The material and methods is divided into four sections: (1) the angiographic system Integris BH 5000 (Philips, Hamburg, Germany) as imaging system and its principles and kinematic structure, (2) the other tools used to measure cardiovascular structure as a position measuring system to navigate the imaging system, and self-developed add-ons to calibrate the angiographic system. (3) is dedicated to the used methods and (4) describes the experiments carried out in preliminary tests.

2.1 Angiographic system

The angiographic system used in the Clinic for Cardiology at the Clinical Center Oldenburg is the Integris BH 5000, manufactured by Philips, Hamburg, Germany. For further work it is necessary to characterize this system first:

The Integris BH 5000 is a biplane angiographic system, consists of two c-arms, patient table, and monitoring devices. The patient table and one c-arm are fixed at the floor. The floor-mounted c-arm has three degrees of freedom. The other c-arm is fixed at the ceiling and has four degrees of freedom (see figure 1). Two rotation joints in each c-arm realize two rotational degrees of freedom (the angles α_C and β_C at the ceiling-mounted c-arm and α_F and β_F at the floor-mounted c-arm). The patient table can adjust three degrees of freedom (translation variables t_{xt}, t_{yt}, and t_{zt}). Additional translation joints are integrated in each c-arm to decrease the distance between image intensifier and x-ray source (translation variables t_{2C} and t_{2F}). Hence, imaging is possible closely to the patient. An extra translation joint is available for the ceiling-mounted c-arm (translation variable t_1).

In the following the kinematic structure of the ceiling-mounted c-arm is presented because of its complexity. Kinematic structure of the floor-mounted c-arm is quite evident and concludes of the kinematic structure of the ceiling-mounted c-arm.

The kinematics of the ceiling-mounted c-arm is modeled as a sequence of the following joints:

- *Joint A*: Translation of the c-arm at a ceiling-mounted rail system.
- *Joint B*: Rotation around the middle point of the c-arm, the so-called iso-center of the central beam. The rotation is described by angle variable α_C. The angle can be changed in the interval [0°, 90°]; vertical orientation defines 0°.
- *Joint C*: Rotation perpendicular to the axis of joint B. The angle, described by variable β_C, can be changed in the interval [-45°, 45°]; perpendicular orientation to the patient table defines 0°.
- *Joint D*: Translation of the image intensifier along the axis of central beam. The translation is described by variable t_{2C}. Possible translational displacements to describe a distance to x-ray source are in the range of [87 cm, 130 cm].

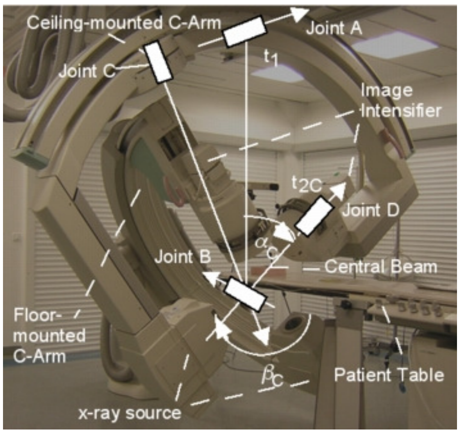

Fig. 1. General setup of the angiographic system with two c-arms and the joint variables for the ceiling-mounted c-arm [5]

2.2 Additional tools

Beyond angiographic system different tools are used to reach the specified goal. First of all there is the position measuring system Polaris (NDI, Ontario, Canada) with its help the measuring of space coordinates of special tools is possible. The special tools are provided with passive markers, which reflect infrared light to the measuring camera. The positions of a set of markers are measured by triangulation. Every tool, which will be tracked by position measuring systems, has to provide at least three markers.

To be able to track the position of x-ray image intensifiers special measurement facilities were constructed and produced - the so-called localizers. The x-ray sources can be tracked by applying planar rigid bodies to the boxes of the sources.

Software was developed to collect the positioning data from NDI's Polaris system and grab radioscopic biplane images from Philips' angiographic system.

Beside these materials for measuring cardiovascular structure other materials were produced to calibrate the system and guarantee the assigned accuracy. The calibration of the angiographic system can be carried out with special facilities, as there is an aluminum grid, to determine the pincushion distortion of radioscopic projection images and two 290 mm rigid polyvinyl chloride (PVC) rods to examine the deviation of the central beam. The grid was prepared with one 5-mm-hole (center), 413 3-mm-holes, and 1264 1.5-mm-holes with a distance of 6 mm to each other.

2.3 Methods

First methods are described, which display possible error sources as there are geometrical image distortions and deviation of central beam. Then the spatial measurement and its principles are specified [5].

In the radioscopic projection image of the aluminum grid an additional virtual grid was inscribed. The distortion can be described as a vector from the center of gravity to the corresponding intersection in the virtual grid. The lengths of these vectors were presented in pixels, representing errors.

Another possible error is the deviation of central beam. The method to show the deviation of central beam is the intersection of lines, which pass the centers of gravity at top and bottom of the PVC-rods. The point of intersection represents the projection of the central beam.

The position measuring system is used to determine the position and orientation of the image intensifiers (in fact the localizers *loc1* and *loc2*) in the coordinate system of the camera *cam*. After initial registration of the image coordinate systems *ima1* and *ima2* at the image intensifiers the transformation between the images can be determined:

$$ {}^{ima1}\mathbf{T}_{ima2} = \left({}^{cam}\mathbf{T}_{loc1} \cdot {}^{loc1}\mathbf{T}_{ima1} \right)^{-1} \cdot {}^{cam}\mathbf{T}_{loc2} \cdot {}^{loc2}\mathbf{T}_{ima2} \tag{1} $$

For the calculation of the projection vectors to possible pixels in an image the position of the x-ray source is determined in the next step. Using the variable t_2 as a translation along the normal vector beginning at the center of the image:

$$ {}^{ima}\mathbf{p}_{xr} = pm \cdot \begin{pmatrix} x_{center} \\ y_{center} \\ 0 \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ t_2 \end{pmatrix} \tag{2} $$

The factor *pm* is the conversation of pixels to length in mm. This factor is determined during image registration process. The position A relative to the coordinate system *ima1* can be determined using the vectors of two corresponding projections points in image 1 and image 2. The point of intersection between these projection vectors represents the position in space. For it the following linear equation system has to be solved:

$$ {}^{ima1}\mathbf{p}_{proj1} + d_1\, {}^{proj1}\mathbf{e}_{xr1} + d_2 \left({}^{proj1}\mathbf{e}_{xr1} \times {}^{proj2}\mathbf{e}_{xr2} \right) = {}^{ima1}\mathbf{p}_{proj2} + d_2\, {}^{proj2}\mathbf{e}_{xr2} \tag{3} $$

The variables d_1, d_2 and d_3 are the distances between the images and the intersection point.

The length of a structure can be determined by two points in image 1 and the two corresponding point in image 2. Two points of intersection are the results; the distance between these points is the measured length.

2.4 Experiments

Experiment 1 (pincushion distortion): A radioscopic projection image was recorded while the aluminum grid was mounted to an x-ray image intensifier. The regular structure of the aluminum grid, which was described by the holes, was distorted in the radioscopic image (see figure 2). An overlaying virtual grid illustrates the distortions.

Experiment 2 (deviation of central beam): The two PVC-rods were screwed on the mounted aluminum grid. Radioscopic images were taken from different angles. The intersection of the straight lines through focal points of top and bottom of the rods characterize the projection point of the central beam.

Experiment 3 (measurement): In a grabbed image significant points can be marked (ROI) e.g. the diameter of a vessel. In the corresponding image of the biplane angiographic system the points belonging to ROI were marked too. These points in an image coordinate system in pixels have to be registered to the surface of their image intensifiers in a space coordinate system in mm. Vectors from these points forward to the x-ray source model the rays of x-ray radiation. The point of intersection of two beams (i.e. two vectors) is the position of the rim of vessel for example. The mathematical construction of the special points of a vessel the diameter can be measured as the distance from one rim of vessel to the other.

3 Results

The experiments 1 and 2 show the possible error factors of the resulting images. The pincushion distortion of the images can be measured as the length of error-vectors. In different angles (0°/0°, 30°/0°, and 90°/0°) the mean errors differs from 7.2 pixels (0°/0°), and 6.2 pixels (30°/0°) to 6.0 pixels (90°/0°). The maximum error are 27.7 pixels (0°/0°), 26.9 pixels (30°/0°), and 27.8 pixels (90°/0°). The error vectors are oriented away from the image center. The relative errors between different angles are small and will be neglected (see figures 2 and 3). The pincushion distortion will be corrected in the projective radioscopic images to resolve undistorted images. The distortions have an effect on measuring the length of cardiovascular structure.

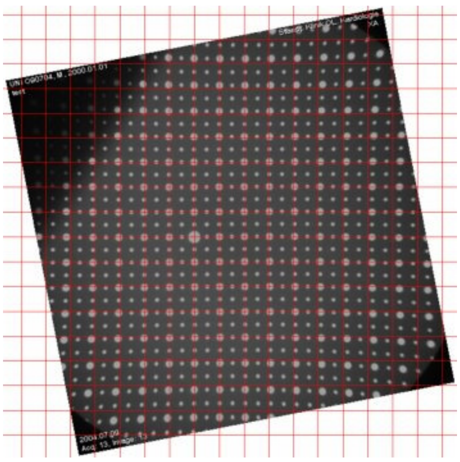

Fig. 2. Geometrical distortions of an x-ray image determined by a regular aluminum grid with overlaying virtual grid [5]

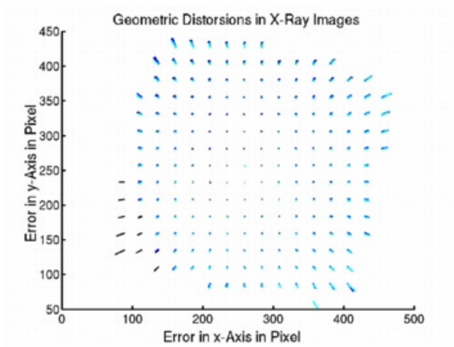

Fig. 3. Error vectors of three x-ray images determined by comparing the known grid positions with the positions of the center of gravity of projected holes at the image [5]

In experiment 2 the deviation of central beam was determined. The points of intersection, representing the position of the central beam, cover an area of approximately 10 mm by 10 mm (see figure 4). The movement of central beam from left to right was caused by descending angle α_C = [90°, 0°]. The angle β_C = [-45°, +45°] causes a movement from bottom to top. The correction of deviation of the central beam during calculation has only slightest effects on the measuring result. The experiment was carried out using the ceiling-mounted c-arm.

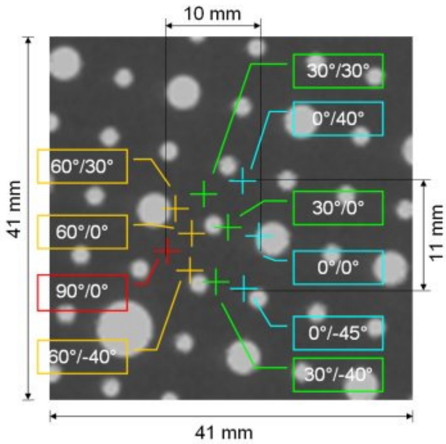

Fig. 4. Deviation of the central beam for different configurations of α_C /β_C [5]

The measurement of diameters at top and bottom (see figure 5) of copper wires with different thicknesses (diameter of 3.6 mm and 4.1 mm) shows following results. The measurement was carried out with and without the effect of pincushion distortions. The corrected measurement results show the measurement with distortion and the uncorrected results represent the same measurements without distortion correction. For each measurement result the deviation was specified absolutely (mm) and relative.

Table 1. Measurement results of diameters with and without distortion correction

	real [mm]	corrected [mm]	dev. [mm]	dev. [%]	uncorrected [mm]	dev. [mm]	dev. [%]
A_{top}	4.1	4.1	0	0	4.0	-0.1	-2.44
A_{bottom}	4.1	4.2	0.1	2.44	4.4	0.3	7.32
B_{top}	4.1	4.5	0.4	9.75	4.7	0.6	14.63
B_{bottom}	4.1	4.4	0.3	7.32	4.5	0.4	9.75
C_{top}	3.6	4.0	0.4	11.11	3.9	0.3	8.33
C_{bottom}	3.6	3.6	0	0	3.9	0.3	8.33
D_{top}	3.6	3.7	0.1	2.78	3.7	0.1	2.78
D_{bottom}	3.6	4.0	0.4	11.11	3.9	0.3	8.33
Mean			0.2	5.56		0.3	7.74

The effects of central beam deviation were examined by changing the variables $x_{central}$ and $y_{central}$ (see equation 2, page 4) to the corners of the measured area. The values were presented with the measured result with distortion correction, using the image center as point of projection of the central beam (same results in table 1). In reference to these results the deviations were calculated:

Table 2. Effects on measurement results of diameter caused by the deviation of central beam

	center [mm]	upper left corner [mm]	upper right corner [mm]	lower left corner [mm]	lower right corner [mm]	max. dev. [mm]	max. dev. [%]
A_{top}	4.1	4.1	4.1	4.1	4.1	0	0
A_{bottom}	4.2	4.2	4.2	4.2	4.2	0	0

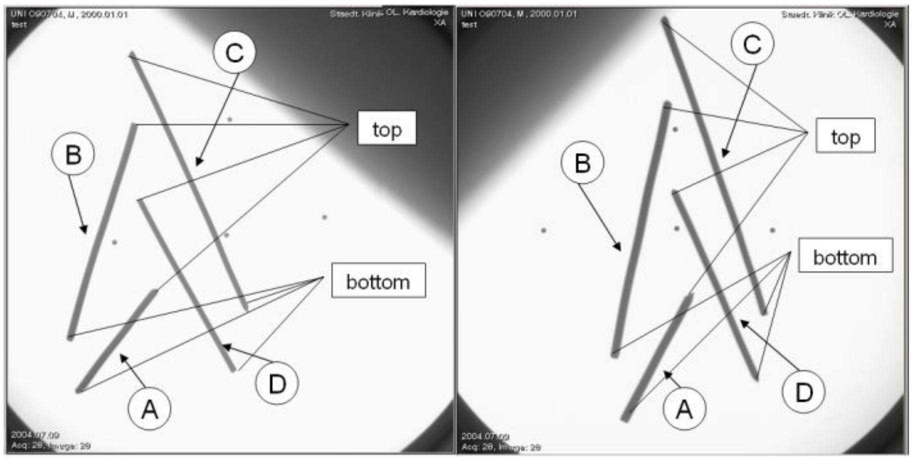

Fig. 5. Measurement of lengths of diameter of copper wire images by two projections - left hand side is the image taken by the floor-mounted c-arm (frontal) and right hand side the image taken by the ceiling-mounted c-arm (lateral)

4 Discussion

Some interfering factors, which derange the measurement results, are less significant as supposed to be. E.g. the deviation of central beam doesn't have significant effects on the measurement result. In contrast to that, the correction of pincushion distortion provides more exact results (mean error 5.56 % in corrected images, mean error 7.74 % in distorted images).

The measurement of length provides in preliminary tests an adequate accuracy of at least 0.4 mm. The measurements of length were carried out at phantoms, representing cardiovascular structures. As a typical examination in the field of cardiology the diameter of a vessel (i.e. the copper wire) has to be determined. The maximum error of 11.11% provides a measured diameter which is larger than the real one. In relation to actual treatments this improves the current determination of vessel diameter, because at least less x-ray images will be produced and the x-ray radiation to patient and medical staff will decrease.

In future work these results will be improve under statistical reliance. In addition other possible error sources, e.g. the deflection of kinematics, will be integrated in correction process. The dedicated influences of errors have to be classified.

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