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New method for geometric calibration and distortion correction of conventional C-arm ☆

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ABSTRACT

Image distortion correction and geometric calibration are critical operations for using C-arm DSA (Digital Subtraction Angiography) images to digitally navigate vascular interventional surgery. In traditional ways, C-arm images are corrected with global or local correction methods where a supposed virtual ideal image is needed, and then the corrected images are utilized to calibrate the C-arm with a pin-hole model. In this paper, we propose a new method to calibrate the C-arm with a nonlinear model and to improve navigation performance. We first calibrate the C-arm with a nonlinear model and then the distortion correction is accomplished without virtual ideal image. In this paper, the nonlinear model of C-arm imaging system is addressed at first, and then the C-arm is calibrated with a two-stage method. In the first stage, the C-arm is calibrated with the markers in image center by RAC (radial alignment constraint) method, and in the second stage the calibration parameters are optimized with Levenberg-Marquadt algorithm by minimizing the sum of the square of difference between all markers' real distorted positions and their theoretical distorted positions in the phantom image. Based on the calibration result, the image distortion can be corrected. To verify our method, experiments were conducted with a conventional DSA C-arm machine in hospital. The errors in distortion correction and 3D (three-dimensional) reconstruction were quantitatively compared with the global polynomial correction method and visual model method, and the results showed that the proposed method had better performance in distortion correction and 3D reconstruction.

1. Introduction

C-arm X-ray machine is widely used for its flexible mobility and perspectives ability to acquire real-time medical X-ray images of the physiological tissue of patient. In C-arm X-ray image based medical robotic system, the C-arm should be calibrated to get 3D information from 2D images [1]. However, images captured by conventional C-arm have inherent geometric distortion [2], mainly including pincushion distortion, sigmoidal distortion and local distortions [3–5]. These distortions should be corrected for accurate navigation.

Traditionally, the distortion correction is conducted at first. Then the corrected images are used to calibrate the C-arm with the pinhole model [6]. There are two main types of conventional correction methods: local method [5,7] and global method [8–10]. Soimu et al. [11], designed a method by combining both global and local methods. Yan et al. [2] proposed a method based on moving least squares and polynomial fitting. They also came up with a hybrid method integrating the moving least-squares method and multilevel B-spline approximation approach [12]. For these traditional correction methods, both the distorted and the undistorted image positions of calibration phantom markers are needed. The distorted positions can be extracted from the real images, while their undistorted positions must be acquired by special ways. Most researchers [5,13–15] assumed that the phantom plane was parallel to the imaging plane of C-arm input screen and that distortions at the central region of the C-arm image were very small. The ideal positions of markers were deduced from the markers' positions in the central image region. As the image plane of input screen is virtual and invisible, it is hard to guarantee that the plane of phantom is parallel to it. In [22] we compared the installation of phantom between with and without a bubble level. The result showed that directly installing the phantom resulted in larger distortion correction error than installing under help with a bubble level. But the installment of phantom with a bubble level help was complex and took longer time than directly installment. Furthermore, sigmoidal distortion is particularly bigger in the center region of the image than the border area [16]. Gronenschild

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pointed out that computation of the ideal image from central markers in the distorted image is unreliable [5].

Previous studies focused on distortion correction and the distortion correction errors were analyzed generally. Since pinhole model is linear model, few discussed about the 3D reconstruction or localization error with C-arm. But in fact, the actual imaging procedure of C-arm is nonlinear. This should be considered to improve the localization accuracy with C-arm.

In our previous study [17] a visual model (VM) based method was proposed to solve geometric calibration and image distortion correction, in which the C-arm was regarded as a nonlinear CCD (Charge Coupled Device) camera. In that work, we calibrated the C-arm with two steps. In the first step we just considered the radial distortion and calibrated the C-arm with Tsai's RAC method. In the next step, we took into account of the decentering distortion and thin prism distortion, and optimized the calibration using the result in the first step as initial value. After calibration, the C-arm image distortion can be corrected with the calibrated image center and distortion parameters. It worked but the result was not ideal, because the sigmoidal distortion of C-arm is different from the decentering distortion and thin prism distortion of a CCD camera lens.

In this paper, we improve the VM method by introducing a revised nonlinear projection model of C-arm. With the improved method, the distortion error is decreased and the localization accuracy is improved. We firstly introduce the nonlinear model based geometric calibration of C-arm and image geometric distortion correction, then compare it with traditional global polynomial (GP) method and VM method in aspect of distortion error and distance reconstruction error. The results show that the proposed method has a better performance than GP and VM. The proposed method is a vital basis of the IGS (Image Guidance System) of RVIR (Remote Vascular Intervention Robot) [18] which has been validated by animal clinic experiment [19].

The proposed method differs from previous techniques in three aspects: First, C-arm is calibrated before image distortion correction, which is reversed to the traditional ways, therefore their applied mechanisms are also different. Second, we do not need to suppose the phantom to be parallel to the image plane of the C-arm and to compute the virtual ideal image using positions of phantom markers in central image, which is necessary in traditional studies but whose accuracies are controversial. Third, C-arm calibration is not based on pinhole model but a revised nonlinear model. With this method, we can install the calibration phantom directly and quickly, without need of a bubble level's help.

2. Nonlinear model based geometric calibration for C-arm

2.1. Non-linear projection model of C-arm imaging system

In a C-arm imaging system, the X-ray beams transmitted by X-ray tube penetrate through an object, e.g. patient body, project onto the input screen of X-ray detector to form an X-ray image, as shown in Fig. 1. The projection model of an ideal C-arm is pinhole model [6]. If we use $\tilde{\mathbf{x}}$ to denote the homogeneous coordinate of $\mathbf{x}$, then a 3D point $\tilde{\mathbf{P}} = [X, Y, Z, 1]^T$ and its ideal image projection point $\tilde{\mathbf{p}} = [u, v, 1]^T$ has the following relation:

$$s\tilde{\mathbf{p}} = \mathbf{M}\tilde{\mathbf{P}} \tag{1}$$

where s is a scalar factor and $\mathbf{M}$ is the 3×4 projection matrix.

However, the real C-arm imaging system exists geometrical distortions, including pincushion, sigmoidal and local distortions. Among them, the local distortion is irregular for different C-arm input screen [13], but it is rather smaller compared with the other two distortions. Therefore it is often neglected [14]. Let $\mathbf{p}_d$ be the actual projection position of point $\mathbf{P}$. $\mathbf{p}_d$ depends on C-arm distortion and can be described as

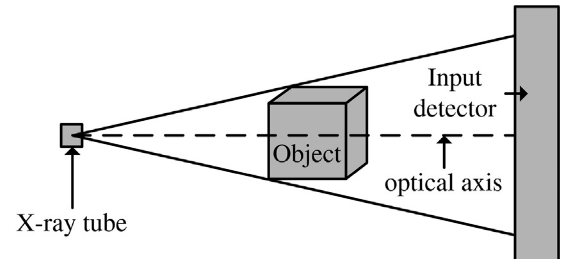

Fig. 1. C-arm imaging system.

$$\mathbf{p}_d = \mathbf{p} + \delta, \quad \delta = \delta_p + \delta_s \tag{2}$$

where δ is the total geometrical distortion, including pincushion distortion δ_p and sigmoidal distortion δ_s.

2.2. C-arm distortion model

Pincushion distortion is caused by the curved surface of input screen, which is similar to a CCD camera lens. Previous studies [2,7,13] implied that pincushion distortion could be modeled as that of a CCD. Weng et al.'s [20] pincushion distortion model is chosen in our technique and can be expressed by the following form:

$$\begin{cases} \delta_{px} = x_u(k_1 r^2 + k_3 r^4 + k_5 r^6 + \ldots) \\ \delta_{py} = y_u(k_2 r^2 + k_4 r^4 + k_6 r^6 + \ldots) \end{cases}, \quad r = \sqrt{x_u^2 + y_u^2} \tag{3}$$

where (x_u, y_u) is the undistorted position and k_1,k_2,k_3,…are the coefficients of pincushion distortion.

We used the first item in each of the above equations to model the pincushion distortion of C-arm. Therefore, k_1 and k_2 represent the coefficients of pincushion distortion of C-arm.

Sigmoidal distortion is introduced by the electron optics between the input and the output phosphor of the input screen and the interaction with external earth's magnetic field or other stray magnetic fields around the input screen. It changes considerably in pattern and magnitude when the C-arm position changes.

Since for sigmoidal distortion the tangential displacement is different along the radial displacement, we reckon that sigmoidal distortion includes rotation and displacement effect. Therefore we model the sigmoidal distortion by the following function:

$$\begin{cases} \delta_{sx} = (x_u \cos\theta - y_u \sin\theta)(1 + t/r) - x_u \\ \delta_{sy} = (x_u \sin\theta + y_u \cos\theta)(1 + t/r) - y_u \end{cases}, \quad r = \sqrt{x_u^2 + y_u^2} \tag{4}$$

where θ and t are the magnitudes of rotational and translational effects respectively (see Figs. 2 and 3).

Rotational and translational effects of sigmoidal distortion vary from one position to another. The earth's magnetic field is unstable because of different locations and time, meanwhile, the internal electronic beam of C-arm could not be acquired accurately. Therefore, it is difficult to find the accurate relationship between distortion parameters and their positions. In order to minimize the localized effect, we utilized the following n-order polynomial to calculate k_1, k_2, θ and t separately.

$$\vartheta = \sum_{p=0}^{n} \sum_{q=0}^{n-p} a_{pq} x_u^p y_u^q \tag{5}$$

where n is polynomial degree, and a_{pq} is the polynomial coefficient, and ϑ represents k_1, k_2, θ and t.