Automated hybrid TACT volume reconstructions

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Abstract A new method for automated detection of reference points in single optical images is introduced. The detection process is based on Hough transforms for ellipses and lines. Experiments show that the algorithm is flexible with regard to different experiment setups and robust against variable lighting conditions. The new method allows the automated application of Tuned-Aperture Computed Tomography (TACT), which provides volume reconstructions from positions of reference points seen in planar radiographs. A hybrid system is used to replace radiographic with optical references.

1 Introduction

Tuned-Aperture Computed Tomography® (TACT®) allows volume reconstructions from multiple two-dimensional X-ray projections. These projections can be produced from unknown and / or random angles and positions [1]. A set of object features (*landmarks*) is used to determine the relative projection geometry. Usually, radiopaque spheres are attached as landmarks to the object, and their images are recognized reliably as fiducial references (*fiducials*) in all projections. A unique feature of TACT is that explicit determination of landmark positions in space is not necessary. In contrast, the reconstruction is based on relative positions of fiducials in respective projections only [1].

For a reconstruction based on unconstrained geometries, TACT requires up to six landmarks of two distinguishable types. Therefore, establishing an appropriate configuration can be challenging. Manual localization of fiducials is time-consuming and also problematic when local contrast is low. Other shortcomings of TACT include decreased reconstruction quality resulting from landmarks that mask anatomic details and the limited range of projection geometries (aperture).

Radiopaque landmarks can be replaced by radiolucent markers if a hybrid imaging system consisting of a radiographic system plus an optical camera is used. The camera is rigidly attached to the X-ray source and takes photographs of the scene [2]. Appropriate normalization made possible by the addition of four landmarks allows correction for projective artifacts produced when the optical imaging plane and the radiographic sensor are not parallel.

The task of automated fiducial detection is not new. Related research has been done in the field of computer vision, where fiducial positions are often used to determine the location and orientation of the camera [3]. Many approaches such as [4,5] assume temporal coherence of camera movement and use Kalman filtering or the Condensation algorithm, where fiducial positions in the next frame are predicted based on positions in the current frame. As such, these approaches require video sequences. Other approaches utilize information obtained from non-vision modalities such as a magnetic tracker or an inertial sensor to restrict the search space in the vision module (e. g., [6,7]). In contrast, the system presented here demands analysis of sequences of relatively uncorrelated images from a single camera because, in general, the camera position changes abruptly and unpredictably between shots.

This work presents a method for automated detection of fiducials in optical projections as produced by a hybrid TACT imaging system. This eliminates the need for radiopaque landmarks and overcomes other shortcomings of conventional TACT.

2 Method overview

Landmark design. Fig. 1 shows the design of an optical landmark. A circle is chosen as the basic form. Circles appear as ellipses when projected onto the camera's imaging plane. However, the projection of a circle's center does not coincide with the center of the corresponding ellipse. Consequently, circle centers are marked. The circle's interior region is divided into four quadrants, two of which are black and the other two have a certain color. The intersection of the discontinuities between adjacent quadrants of contrasting colors denotes the center of the circle.

The hue of colored quadrants is used to distinguish different landmarks. White point information is included in the design of landmarks to reduce sensitivity to changes in illumination. This is accomplished by circumscribing the inner circle with a white ring delimited peripherally by a thin black line.

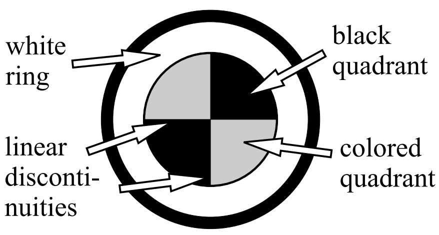

Figure 1. Design of optical landmarks.

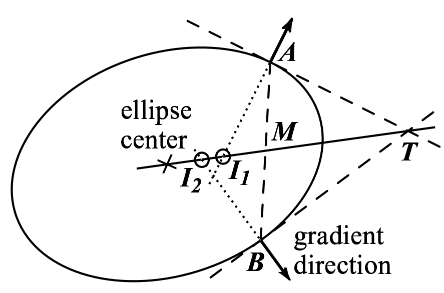

Figure 2. Construction of lines for the detection of the ellipse center.

Calibration. A calibration mechanism that includes the number and colors of respective landmarks is defined to provide flexibility with regard to landmark constellation, imaging equipment, and lighting conditions. Information is obtained from a single optical projection under expected lighting conditions using the intended optical imaging system. Hues of respective landmarks are recorded in this image after white point correction. In addition, estimates of the largest major and smallest minor diameter are documented. These are obtained from user input. This calibration procedure is necessary only once for each combination of landmark arrangement, optical equipment, and lighting condition.

Fiducial detection. A fiducial candidate is a complete bright ellipse on a dark background (white ring delimited peripherally by a thin black line). The assumption of complete ellipses allows speed optimization and a higher degree of reliance on a successful detection. First, all candidates for being a fiducial are identified in intensity images of reduced size. At this stage, high sensitivity is required, but low specifity is acceptable. Local gradients and their directions are detected using the Canny edge detector such that gradient vectors point orthogonally from the brighter to the darker side of the edge. Subsequently, ellipses are localized by means of a Hough transform (HT) for ellipses [8]. Here, only bright ellipses on a dark background are regarded.

Thereafter, detected ellipses are converted back into corresponding parameters in the original image space domain. Now, only the region within a candidate ellipse is considered, and a dark ellipse on a bright background is searched by means of another HT for ellipses (inner circle circumscribed with a white ring). Inside this ellipse, two intersecting lines are detected by means of a HT for lines. Their intersection determines the exact location of the fiducial. The lines define four quadrants, and the hue of the fiducial candidate is computed from the white point corrected average color of the two colored quadrants. The candidate is rejected if any expected parts cannot be detected.

Verification. A fiducial candidate is considered to be an actual fiducial if it fulfills certain homogeneity criteria for the inner circle quadrants. The assignment of found fiducial candidates to landmarks is done according to the hue. The detection of fiducials is rejected if a bijective correspondence of detected fiducials and expected landmarks cannot be established.

3 Implementation

The extraction of elliptical shapes is achieved by means of a HT, which collects votes for parametrically described shapes in an *accumulator array*. In the case of ellipses, the parameter space becomes five-dimensional. However, the dimensionality of the problem is reduced by splitting the detection process into three subsequent steps: detection of the center, orientation, and axis lengths. This reduces the dimensionality of each step to only one or two [8].

The detection of the center is based on a general property of ellipses. For any two points A and B on an ellipse, the line through the intersection T of their tangents and the mid-point M between A and B passes through the center of the ellipse (Fig. 2). Thus, for all pairs of edge points in the image such a line $\overline{TM}$ is constructed, and cells along the line are incremented in a two-dimensional accumulator array with axes for center coordinates x_0 and y_0 [8]. Then, the center coordinates of the ellipse are defined by a peak in the accumulator array.

In [8], parameters of lines $\overline{TM}$ are determined, and peaks are found using a focusing algorithm. However, this procedure is equivalent to incrementing the value of accumulator cells along a line of infinite length. Accordingly, points erroneously vote for ellipse centers far away from their position—and this may lead to spurious accumulator peaks. In this work, the length of line segments is half the maximal expected major diameter, which is known from calibration. Line segments lie on $\overline{TM}$, start at M, and direct away from T. If A and B actually are points belonging to the same ellipse, M is located inside the ellipse. Consequently, the center cannot be further away than half the length of the major axis (Fig. 2).

Gradient direction at A and B and the position of A and B relative to the line $\overline{TM}$ is used to make the distinction between bright ellipses on a dark background and vice versa. Let us define $\overrightarrow{v} := T - M$ and denote gradient vectors at A and B as $\overrightarrow{g_A}$ and $\overrightarrow{g_B}$, respectively. Then, we can solve the following equations for the unknown scalars l and r to determine the position of intersections I_1 and I_2 relative to A and B and their gradient directions (Fig. 2):

$$A + l \cdot \overrightarrow{g_A} = M + m \cdot \overrightarrow{v} \tag{1}$$

$$B + r \cdot \overrightarrow{g_B} = M + s \cdot \overrightarrow{v} \tag{2}$$

For bright ellipses on a dark background, l and r are less than zero. For the opposite configuration, l and r are greater than zero. If l and r have different signs, A, B do not belong to the same ellipse, and this pair of points is disregarded.

For the detection of the orientation of the ellipse and the lengths of the semimajor and the semiminor axis, we follow the procedure described in [8].

4 Results

The method is applied in two experiments under different lighting conditions with 37 and 20 projections, respectively. All optical fiducials are detected successfully without any spurious responses. Resulting reconstructions are visually compared to those obtained using conventional TACT and appear to be identical. For an experiment setup with six landmarks and images of size 1930 x 1644 pixels, the algorithm runs on standard hardware (Intel® Pentium® III - M, 933 MHz, 512 MB RAM) in a mean time of 36.7 seconds per image using the Java™ 2 Platform Standard Edition, Version 1.3.

5 Discussion

In this work, a new algorithm is introduced that allows robust detection of optical fiducials for hybrid TACT volume reconstruction. Resulting from the calibration procedure, the method is flexible in terms of different landmark constellations and digital cameras. Also, it is robust against variable lighting conditions. Therefore, TACT can now be used more conveniently in a wider range of clinical applications. In particular, larger apertures become possible. In addition to optical markers, radiopaque landmarks are attached to the object in one of the experiments. In this case, the complete set of radiopaque landmarks is visible in only 20 of 37 radiographs, but all optical landmarks are apparent, and fiducials are detected correctly in all optical projections.

Although implemented in Java, the runtime of fiducial detection is about half the time required for the repositioning of the patient and the coupled system of X-ray source and optical camera, which takes about one minute. Hence, the computations are performed in "real time" during successive image acquisition. The method neglects geometric distortions of the optical system. If necessary, geometric correction must be performed prior to fiducial detection. The precision of the fiducial detection determines the quality of volume reconstructions. It is limited only by the precision of the detection of the intersection of the lines or the center of projected radiopaque landmarks for hybrid or conventional TACT, respectively. This is mainly dependent on the resolution of the system, i. e., the number of pixels divided by the size of the field of view. For hybrid TACT, the latter is affected by the spatial setup including the position of landmarks and the focal length of the camera. Hence, improved precision is expected for hybrid TACT. A comprehensive analysis of the precision is planned for the future.

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