An Algorithm for Tracking Microcatheters in Fluoroscopy

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Currently, a large number of endovascular interventions are performed for treatment of intracranial aneurysms. For these treatments, correct positioning of microcatheter tips, microguide wire tips, or coils is essential. Techniques to detect such devices may facilitate endovascular interventions. In this paper, we describe an algorithm for tracking of microcatheter tips during fluoroscopically guided neuroendovascular interventions. A sequence of fluoroscopic images ($1,024 \times 1,024 \times 12$ bits) was acquired using a C-arm angiography system as a microcatheter was passed through a carotid phantom which was on top of a head phantom. The carotid phantom was a silicone cylinder containing a simulated vessel with the shape and curvatures of the internal carotid artery. The head phantom consisted of a human skull and tissue-equivalent material. To detect the microcatheter in a given fluoroscopic frame, a background image consisting of an average of the four previous frames is subtracted from the current frame, the resulting image is filtered using a matched filter, and the position of maximum intensity in the filtered image is taken as the catheter tip position in the current frame. The distance between the tracked position and the correct position (error distance) was measured in each of the fluoroscopic images. The mean and standard deviation of the error distance values were 0.277 mm (1.59 pixels) and 0.26 mm (1.5 pixels), respectively. The error distance was less than 3 pixels in the 93.0% frames. Although the algorithm intermittently failed to correctly detect the catheter, the algorithm recovered the catheter in subsequent frames.

KEY WORDS: Catheter motion tracking, vascular intervention, fluorography, cerebral artery, image subtraction, microcatheter, navigation system

INTRODUCTION

A large number of endovascular interventions are performed in patients with intracranial aneurysms. In these interventions, coils or stents

are transported via a microcatheter under fluoroscopic guidance, i.e., using two-dimensional (2D) projection fluoroscopic images. It is important to recognize where the microcatheter is located in the vascular structure because a coil will cause a stroke if placed in the wrong position. Knowledge of the 3D position of the guidewire, the catheter tip, or the microcatheter tip relative to the vascular structures may facilitate interventions. However, determination of the 3D catheter position is difficult because fluoroscopic images are not only two-dimensional but also noisy.

Magnetic resonance imaging-based navigation systems have been investigated.¹⁻⁶ These systems can provide accurate 3D information during interventions, but they also require particular hardware and devices. Moreover, special care is needed because of the magnetic fields used. Other

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investigators have proposed methods that allow determination of 3D catheter positions using devices that transmit electromagnetic signals to allow detection and tracking of the catheter tip in the body in conjunction with conventional X-ray angiography systems.⁷⁻⁹ An image-based technique¹⁰ has been proposed for cardiac interventions, which aligns a catheter model with the catheter image in a single-plane C-arm image using the Projection-Procrustes method.¹¹ Research has focused on the quality of fluoroscopic images and the detectability of the catheter.¹²⁻¹⁵ Techniques have been developed to detect and/or track a guidewire in fluoroscopic images during cardiac interventions,^{16,17} and a technique that facilitates endovascular interventions for intracranial aneurysms has been proposed that provides 3D positional information of a guidewire by reconstructing the 3D guidewire from a pair of biplane views.¹⁸ We are developing an image-based system (Computer Assisted Catheter Guide System) to help in navigation of catheters during interventions for intracranial aneurysms. Specifically, this system will provide image-based 3D catheter locations. We have proposed an algorithm to map 2D positions of catheter tips in fluoroscopic images to 3D positions in magnetic resonance angiography data acquired preoperatively.¹⁹ However, for full automation with this system, the catheter must be detected and tracked automatically and accurately in the images.

In this paper, we present an algorithm for tracking of the microcatheter tip in fluoroscopy, which requires only the initial position of the microcatheter tip in the initial frame.

METHODS

An algorithm for tracking the microcatheter tip was developed. For each fluoroscopic image, a background image is generated from the preceding images and is subtracted from the current image, the resulting image is filtered using a filter approximately matched to the catheter tip, and the maximum in the filtered image is taken as the position of the catheter tip. A set of sequential fluoroscopic images of a phantom was obtained as a catheter passed through a carotid phantom. The algorithm was evaluated in terms of accuracy of the positions detected.

Algorithm for Tracking a Microcatheter

In our algorithm for tracking microcatheter tips, a background subtraction technique,²⁰⁻²³ which is used to detect and track cars in images from traffic surveillance cameras, was used. The background subtraction for a signal-below-background image is defined simply as:

$$g_i(x, y) = B(x, y) - f_i(x, y), \quad (i = 1, 2, 3, \dots, n) \quad (1)$$

where the subscript i is the frame number, $f_i(x, y)$ is the current image with the target object, $B(x, y)$ is the background image (mask image) without the target object, and $g_i(x, y)$ is the result image for the i -th frame. Digital subtraction angiography is an example of this technique in clinical use.

However, in the case of fluoroscopy, the catheter or microcatheter is always in the images, and so there is no background image that does not contain the object, except perhaps one of the initial images. Moreover, the patient's position and imaging projection often change during fluoroscopy. Thus, the background image of fluoroscopy should be updated regularly. In addition, the fluoroscopic images are usually noisy. To overcome these problems, a background image is generated using a weighted sum of the frames just previous to the current frame. Equation 1 is thus modified as:

$$g_i(x, y) = \frac{1}{4} \sum_{k=i-4}^{i-1} \{f_k(x, y)\} - f_i(x, y), \quad (i = 5, 6, 7, \dots, n) \quad (2)$$

We call this technique the averaged-image-subtraction technique (AIST).

An algorithm for microcatheter tip tracking was developed using the AIST. An overview of the algorithm is shown in Figure 1. This algorithm requires manual indication of the initial microcatheter tip position, P_{i-1} , in the fluoroscopic image $f_{i-1}(x, y)$ at the start of tracking. For each frame in the sequence, a 41×41 pixel region-of-interest (ROI) centered on the most recently identified catheter tip position is extracted from each of the current frames, $f_i(x, y)$, and the four previous frames, $f_{i-1}(x, y)$ to $f_{i-4}(x, y)$. The size of the ROI is based on the maximum distance of the catheter tip

Fig 1. Scheme of the microcatheter tracking algorithm.

between the frames (see Fig. 5). The extraction of a local region speeds up the analysis, to allow 30 f/s updating of the catheter position. We chose four as a compromise to reduce the noise by a factor of 2. The AIST is performed using the extracted images. The background image is generated, and the current image is subtracted from it.

Convolution is performed on the image resulting from the AIST with a 9×9 kernel to enhance the catheter tip signal and to detect its position. The kernel filter may be effective in cases in which background signals, such as bony edges, are not reduced sufficiently because of movement of the patient or the table. The kernel (Fig. 2) is based on the shape of the measured catheter tip in

fluoroscopic images. The catheter tip is almost a 5×5 square in the fluoroscopic images, so that the 5×5 pixels at the center of the kernel have positive values and the others out of the square are negative. To deal with rotated catheter tips, four pixels just out of the square have positive values. The maximum intensity position is identified automatically in the template-filtered image and is taken as the position of the microcatheter tip in the current frame.

The AIST enhances the signal intensity of moving objects and suppresses that of stationary objects. As a result, the signal intensity of the microcatheter tip is substantially reduced if the microcatheter does not move. Therefore, the background image is not updated for the subsequent

-0.125	-0.125	-0.125	-0.125	-0.125	-0.125	-0.125	-0.125	-0.125
-0.125	-0.125	-0.125	-0.125	0.125	-0.125	-0.125	-0.125	-0.125
-0.125	-0.125	0.5	0.5	0.5	0.5	0.5	-0.125	-0.125
-0.125	-0.125	0.5	0.5	0.5	0.5	0.5	-0.125	-0.125
-0.125	0.125	0.5	0.5	0.5	0.5	0.5	0.125	-0.125
-0.125	-0.125	0.5	0.5	0.5	0.5	0.5	-0.125	-0.125
-0.125	-0.125	0.5	0.5	0.5	0.5	0.5	-0.125	-0.125
-0.125	-0.125	-0.125	-0.125	0.125	-0.125	-0.125	-0.125	-0.125
-0.125	-0.125	-0.125	-0.125	-0.125	-0.125	-0.125	-0.125	-0.125

Fig 2. The template filter for enhancement of a microcatheter tip signal.

frame if the following analysis indicates that the catheter did not move. The mean and standard deviation of all pixel values in the image obtained by AIST is calculated. A threshold is set as the mean plus a multiple of the standard deviation. If the current position of the microcatheter tip in the image obtained by AIST has a pixel value of less than the threshold, the microcatheter is taken to have not moved. In addition, if the distance between the position in the current frame and that in the previous frame is less than 3 pixels, the background image is not updated. These processes are repeated, tracking the microcatheter tip throughout the fluoroscopic sequence.

To find the optimal multiple of standard deviation values, two through seven times the standard deviation were applied, and the optimal multiple was determined.

Evaluation

A sequence of 90 fluoroscopic images ($1,024 \times 1,024 \times 12$ bits) were acquired using a CAS-8000 V (Toshiba America Medical Systems Inc., Tustin, CA, USA) C-arm angiography system as a 2.5 French single-marker microcatheter (Fas-tracker-18; Target, Fremont, CA, USA) was passed through a carotid phantom, which was on top of a head phantom (Fig. 3c). The sequence was acquired at 30 frames/sec using pulsed fluoroscopy at 94 kV and 50 mA (the pulse width=3.2 msec). The 7-inch image-intensifier mode was

used (pixel size=0.174 mm). The source-to-image distance was 100 cm, and the magnification was 1.35 times at the tabletop. The carotid phantom was a Sylgard cylinder containing a simulated vessel with the shape and curvatures of the internal carotid artery from just above the carotid bifurcation up to the Circle of Willis (Fig. 3b). The vessel in the carotid phantom was filled with glycerin–water solution. The head phantom consisted of a human skull and tissue-equivalent material (Fig. 3a) and was used to provide the bony background in the fluoroscopic images. After acquisition, the sequence was transferred to a computer for analysis.

The microcatheter tip position in each fluoroscopic image was determined manually, and this position was taken as the true position in the fluoroscopic image. The true positions were in the catheter tips, but may not have been the exact center of the catheter tip, and so the true positions may have shifted by up to about 2 pixels along each of the X and Y axes because the catheter tips measured about 5×5 pixels. Figure 4 shows a frame from the sequence and the user-determined path taken by the catheter tip. The movement of the catheter tip is shown in Figure 5. The distance values in pixels between the catheter tip position in the current frame and that in the former frame are shown in the graph.

The 2D distance between the user-determined position and the position determined by our algorithm (error distance) was calculated in each

Fig 3. The phantoms and the setting for acquisition of the fluoroscopic images. a The carotid phantom, consisting of a tube having curvatures similar to a typical carotid artery fixed in a silicone cylinder. b The head phantom which provided bony background to the fluoroscopic images. c The set-up configuration of the head phantom, carotid phantom, image-intensifier (I.I.), and the x-ray tube in the experiment.

of the fluoroscopic images. The mean error distance was calculated by averaging over all the frames. We considered a position determination to be correct when the error distance was less than 3 pixels (0.522 mm). This error distance was chosen

because the size of the microcatheter tip in the fluoroscopic images was about 5×5 pixels.

The AIST takes the initial four frames to create a background image leaving 86 of the 90 frames for the detection task. The number of frames in

Fig 4. The first frame of the fluoroscopic image sequence (a) and the user-indicated path (white line) and tracked positions (black dots) of the microcatheter tip (b).

Fig 5. Movement of the catheter tip in pixels as a function of frame number.

which our algorithm determined the position correctly was counted, and the percentage of correct detections out of the 86 effective frames was calculated.

RESULTS

The results for two through seven times the standard deviation, calculated from the pixel values in the AIST-result images, are shown in Table 1. The results for 4.5 times and five times the standard deviation were the best. We chose 4.5 times the standard deviation because the mean error immediately became worse over five times the standard deviation, i.e., the mean error for six times the standard deviation was larger than those for two times and three times the standard deviation. Moreover, our algorithm could continue

to track the microcatheter correctly in only one third of the frames when seven times the standard deviation was used.

The microcatheter path in fluoroscopy and the tracked positions of the microcatheter tip are shown in Figure 4(b) for a threshold set as the mean plus 4.5 times the standard deviation. The error-distance results for each frame are shown in Figure 6. The error vectors are shown in Figure 7. The error vectors were calculated as the difference between the true (indicated) position and the calculated position. The directions of the error vectors were normalized by determining the orientation of the error vector relative to the catheter motion vector between the current and previous true positions. The v axis of the graph in Figure 7 is parallel to the catheter motion vectors and the u axis is orthogonal to the motion vectors.

The mean and standard deviation of the error distance values were 0.277 and 0.256 mm, respectively. Our algorithm could detect the microcatheter tip positions in 80 of the 86 frames (93.0%) with errors of less than three pixels. It should be noted that although the algorithm failed for some individual frames, it recovered the catheter tip in subsequent frames, successfully tracking the catheter tip through to the end of the sequence.

The distribution of the error vectors is more spread out in the upper half plane of the graph compared to the lower half plane. This may be a result of setting a search area based on the previous tip position; the catheter tip moved downward in the fluoroscopic images because the microcatheter was pulled during the study.

Table 1. Mean and Standard Deviation of the Error Distances and the Number of Frames in which Detection Succeeded for the Specified Multiples of the Standard Deviation

Multiples of Standard Deviation	Mean Error Distance (mm)	Standard Deviation of Error Distances (mm)	Number of Frames (Err. Dist. <0.522 mm)
2	0.326	0.48	79 (91.9%)
3	0.292	0.28	79 (91.9%)
4	0.282	0.28	79 (91.9%)
4.5	0.277	0.26	80 (93.0%)
5	0.277	0.26	80 (93.0%)
6	0.435	0.54	71 (82.6%)
7	19.4	20	20 (23.3%)

Fig 6. Error distance in millimeter as a function of frame number. The mean and standard deviation (SD) of the distance values are given on the *upper right*.

Except for this trend, the distribution appears random indicating that the algorithm is independent for the direction of catheter motion.

The extracted original images of the 7th, 12th, and 31st frames, the AIST-result images, and the

template filtered images are shown in Figure 8. The 12th frame shows an example of success (Fig. 8a–c). The error distance values in the 7th and 31st frames (Fig. 8d–f and g–i, respectively) were relatively large, so these frames were failures.

Fig 7. Distribution of the error vectors relative to the direction of catheter motion. The error vectors were determined as the difference between the true and calculated catheter positions. The v and u axes are parallel and orthogonal to the catheter motion vectors, respectively.

Fig 8. Examples of successful and failed tracking. a, d, and g Extracted original fluoroscopic images of the 12th, 7th, and 31st frames, respectively. b, e, and h Image results of AIST. c, f, and i Images after template filter convolution. The white arrow in each image indicates the catheter tip or its true position.

DISCUSSION

Our algorithm successfully tracked the microcatheter tip to the end of the fluoroscopic image sequence and detected the correct positions in 93% of the images in the sequence. The mean and standard deviation of the error distance values were 0.277 and 0.26 mm, respectively, indicated accurate tracking.

The error distance values in frames 7 and 31 were relatively large. The microcatheter almost stays the same position between frames 6 and 7, and thus the background subtraction substantially reduced the signal of the catheter tip (Fig. 8e), and noise in the image was identified incorrectly by

the detection algorithm (Fig. 8f). The intensity of the microcatheter after processing in this image was above the threshold, and so was identified as having moved. In frame 30, the microcatheter tip overlapped with bony background structures, which reduced the signal of the catheter tip (Fig. 8g). In this case, no signal was detected (Fig. 8h, i), and the position in the former frame was taken as the current position. However, the microcatheter had in fact changed its position between frame 30 and 31, and so the error distance was substantial.

Catheter tips do not move along image coordinate systems, and the catheter tip did so in most of the sequence. Although the catheter tip in the

template filter is perpendicular, template filtering could enhance the tips and detect the positions in such frames.

The size of the ROI (41×41) extracted from fluoroscopic images was chosen to allow for motion of up to 18 pixels (3.13 mm) between frames (see Fig. 5). The size of this analysis region should be optimized based on clinical experience.

The template filter was designed based on the marker at the distal end of the microcatheter used in this study. To the degree that other markers are similar, this template might be useful for other markers. However, optimal tracking may depend on the agreement of the template and the image of the actual marker or device being tracked. Future studies should be performed to evaluate the means of optimizing this algorithm for other devices as well as to determine the robustness of our algorithm.

Microcatheters are usually pushed and pulled repeatedly in interventions. Pulsatile blood flow can also make the microcatheter tip oscillate. These motions could cause reduction of signal intensities in the AIST images. If a current microcatheter position is the same as that in the mask images, the signal intensity will be reduced. This situation could cause large error or tracking. In general, the microcatheter was only pulled during acquisitions used in this study and there was no pulsatile flow. Yet, there are frames, for example 13 and 38, in which the microcatheter apparently stopped during the acquisition. However, the error distances for both of these frames were 0.2 mm which is less than the mean error distance. These results indicated that this algorithm can deal with the variations in the microcatheter motion.

CONCLUSIONS

We have developed an algorithm to track a microcatheter tip in fluoroscopic images. The algorithm provided accurate position tracking of a microcatheter with a mean error distance of 0.277 mm (1.59 pixels) and standard deviation of 0.26 mm (1.5 pixels). The algorithm detected the positions of the microcatheter tip in 93.0% of the fluoroscopic images. Even when it failed on individual images, it recovered the catheter tip in

later frames, tracking the microcatheter tip until the end of the sequence.

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