Real-Time Extraction of Carotid Artery Contours from Ultrasound Images

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Abstract

This paper presents the developement of a novel, fully-automatic tracking and segmentation system to extract the boundary of the carotid artery from ultrasound images in real-time. The center of the carotid artery is tracked by using the Star algorithm [3]. The stability of the Star algorithm has been improved by using a temporal Kalman filter. A spatial Kalman filter is used to estimate the carotid artery boundary. The idea comes from the well-known problem of tracking a single target in a randomly distributed cluttered environment. Since the method does not employ any numerical optimization, convergence is very fast. The stability and accuracy of the method is demonstrated by tracking the carotid artery over a 30 second sequence of ultrasound images taken during a carotid artery examination.

1 Introduction

Tracking a moving object is one of the functionalities of active vision and has attracted a significant amount of attention in the past few years. One of the interesting applications of object tracking is in ultrasound visual servoing [6], where the motion of non-rigid objects in ultrasound images are tracked by extracting their boundaries. There are several approaches reported for feature tracking in medical imaging (e.g., [5, 2]); however, most of these methods operate on high quality images, such as MRI and CT, and can not easily be applied to ultrasound images which contain speckle. To cope with the problems incurred by speckles in ultrasound images, various algorithms have been developed previously for still images [7, 4]. Of particular interest in the problem of ultrasound visual servoing is the ability to track images in real-time over a long period of time [6]. The problem considered first is that of carotid artery tracking and boundary extraction.

A newly developed algorithm for ultrasound boundary extraction is presented here. The method uses the concept of tracking a single target in the randomly distributed cluttered environment introduced in [1] to extract the boundary of the carotid artery. Since no numerical optimization is involved (in contrast to the Snake methods), the algorithm converges very fast and can be implemented in real-time. The center of the carotid artery is tracked by using the Star algorithm [6]. This method has already been used for a different purpose, namely to detect boundaries of the ventricular cavity in ultrasound images [3]. Additionally, a temporal Kalman filter is used together with the Star algorithm to stabilize the tracking result.

This paper presents the implementation of this feature extracting method in real-time on a sequence of ultrasound images of the carotid artery. Section 2 describes the modified Star algorithm along with the new boundary extraction technique. Implementations results are shown in Section 3. Section 4 concludes with a discussion of the results. Experimental results confirm the accuracy and stability of the method.

2 Feature Tracking in Ultrasound Images

A block diagram of the tracking and the segmentation algorithm is shown in Figure 1. The Star algorithm is used together with a temporal Kalman filter to estimate the position of the carotid artery. A spatial Kalman filtering algorithm uses the centroid coordinates of the carotid artery in order to estimate the location of the carotid artery boundary.

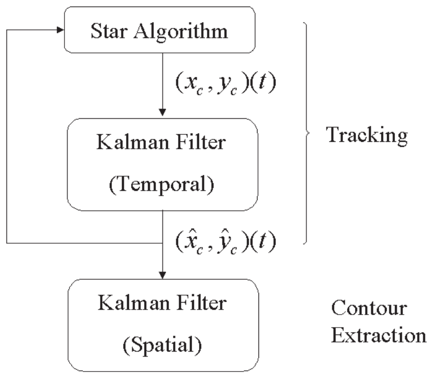

Figure 1: Block diagram of the tracking and contour extraction algorithms. (x_c, y_c) is the estimated position of the carotid artery using the Star algorithm. This information is used in a temporal Kalman filter to predict the location of the carotid artery in the ultrasound image. A spatial Kalman filter is used to extract the boundary of the carotid artery.

2.1 The Tracking Algorithm

The Star algorithm [3] was implemented to track the carotid artery. The algorithm uses an edge-detection filter to detect the carotid artery boundary along rays emanating from a point interior to the carotid artery. It determines (x_c,y_c) (center coordinates of the cavity) as the center of gravity of extracted boundary points.

Although the Star algorithm performs in real-time, it is relatively unstable. This is improved by using a temporal Kalman filter [1]. A constant velocity kinematic model is chosen for the motion of the carotid artery:

$$X(k+1) = \begin{bmatrix} 1 & T \\ 0 & 1 \end{bmatrix} X(k) + V(k) \quad (1)$$

$$Z(k) = \begin{bmatrix} 1 & 0 \end{bmatrix} X(k) + \omega(k) \quad (2)$$

where $X(k) = \begin{bmatrix} x(k) & \dot{x}(k) \end{bmatrix}^T$ is the system state (position and velocity of the carotid artery center), T is the sampling time of the system, $V(k)$ is the process noise vector with covariance $C(k)$, $Z(k)$ is the output of the Star algorithm, and $\omega(k)$ is its error with covariance $D(k)$. It is assumed that the acceleration can be modeled by the zero-mean, white, Gaussian noise. The recursive Kalman filter algorithm [1] is implemented to predict the location of the center point of the carotid artery in consecutive ultrasound image frames.

2.2 Contour Extraction

This section describes the contour extraction method, which is inspired from the original work by [1] for tracking a single target in a randomly distributed cluttered environment, in the spatial domain. The output of the tracking algorithm (centroid coordinates of the carotid artery) at each frame are passed to the contour extraction algorithm. N angularly equispaced radii are projected from $(\hat{x}_c, \hat{y}_c)$. The edge function used in the Star algorithm is applied to all the pixels along each indivual radius. Then, M points along each radius which have the highest edge function value are chosen. Figure 2 shows a schematic diagram of

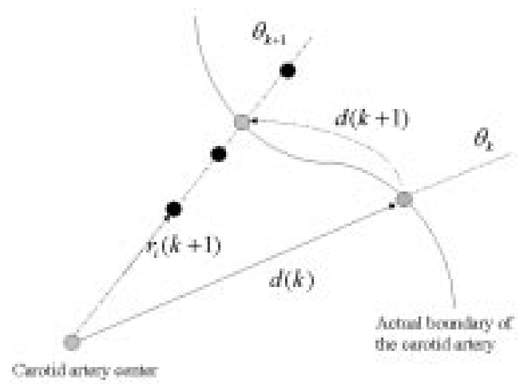

Figure 2: A schematic diagram of the border extraction method; notations are described in the text.

the method. Let $r_i(k+1)$ be the distance of the i^{th} ($i \in 1, 2, \cdots, M$) candidate boundary point along radius $k+1$ from the center point, and $d(k)$ be the radius of the boundary point along radius k, which shows the state of the system at iteration k. Also let $d(k+1)$ be the radius of the boundary at iteration $k+1$, and $z(k)$ be the extracted boundary point (one of $r_i(k)$) at iteration k. The following model could be used to describe the system:

$$d(k+1) = d(k) + \xi(k) \quad (3)$$

$$z(k) = d(k) + \phi(k) \quad (4)$$

where ξ and ϕ are sequences of zero-mean, white, Gaussian process and measurement noise values with covariances $Q(k)$ and $R(k)$, respectively. Since $z(k)$ is unknown, a combination of different candidate boundary points along radius k, $y(k)$, is used in the Kalman filter:

$$y(k) = \sum_{i=1}^{M} r_i(k) p_i \quad (5)$$

where

$$p_i = \text{Prob}\{z(k) = r_i(k)\} \quad (6)$$

p_is can be computed by assuming a normal distribution around the actual boundary for candidate edge points. The edge magnitudes are also incorporated in the calculation of p_is. A modified version of Kalman filter was implemented to deal with this new type of uncertainty [1].

3 Implementation Results

Video-images from an ultrasound examination were obtained. The video images were digitized and processed using a 450 MHz Pentium III PC with a Matrox Meteor frame-grabber. Implementation results show promising performance. The motion of the carotid artery is tracked at 30 frames/second by using the improved Star method, when $C(k) = \begin{bmatrix} 0.0 & 0.002 \\ 0.002 & 0.12 \end{bmatrix}$, and $D(k) = 20$, for all k. The average tracking time is 10 to 30 seconds. The maximum tracking time depends on the quality of the ultrasound images.

Figure 3 shows the estimated boundary of the carotid artery using the contour extraction method, when $R(k) = 20$ and $Q(k) = 1$ for all k. The number of radii is considered 32 and along each radius, 10 candidate edge points are chosen ($M = 10$). A cubic B-spline algorithm has been used to interpolate the estimated boundary points. The sensitivity of the method could be changed by adjusting $Q(k)$ and $R(k)$.

The result of this work shows that the method is more stable than those proposed in [6] and provides better boundary estimation without using any numerical optimization.

4 Summary and Conclusions

A new algorithm has been developed to extract the boundary of the carotid artery in real-time. A modified Star algorithm is used to track the center of the carotid artery. The output of this stage is passed to a contour extraction method which is inspired from a single target tracking algorithm in a randomly distributed cluttered environment in the spatial domain. Implementation results indicate good performance of the method. Further, the method could be extended to consider the shape of the cavity in system model (Equations (3) and(4)). The method is used in our laboratory for the visual servoing for robot-assisted diagnostic ultrasound, as proposed in [6].

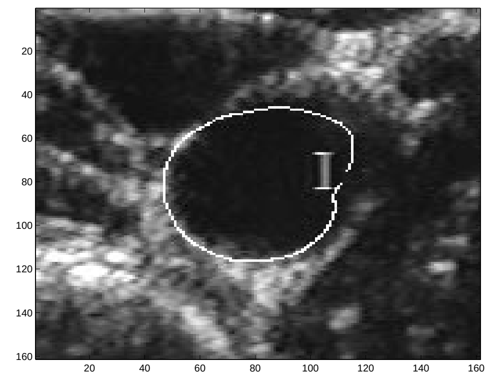

Figure 3: Spatial Kalman filter boundary estimation, using R=20 and Q=1. The algorithm is less sensitive to the change in the boundary.

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