# TRACKING CURVILINEAR STRUCTURES USING ACTIVE CONTOURS AND APPLICATION TO MICROTUBULE VIDEOS

*M. A. El Saban and B. S. Manjunath*

Electrical and Computer Engineering Department, University of California, Santa Barbara
{msaban, manj}@ece.ucsb.edu

**ABSTRACT**

We present a novel active contour-based tracking algorithm for highly deformable and fast moving curvilinear structures. We propose to use line features as external forces for the active contour for the detection phase in the first frame. For the tracking part, we propose a novel approach of detecting motion of the endpoints and then deformation of the other points using the same active contour model used for detection. Estimating the motion at endpoints only has two advantages. First, motion estimation at endpoints is more robust at endpoints and corners, specially in noisy situations. Other points of the curvilinear structure may suffer from the aperture effect. Second, this will allow large deformation in the body of the structure from frame to frame. As an example application, we have tested our algorithm for biomolecular videos in tracking microtubules which exhibit high deformations in noisy video sequences. Experimental results show both quantitatively and qualitatively the good performance of the tracking algorithm

## 1. INTRODUCTION

Curvilinear structures detection and tracking represent important computer vision problems for applications such as road detection, mammographic image analysis, fiber identification, fingerprint image analysis and fibrous microtubules and actin filaments identification. Many techniques have been proposed in the literature to detect curvilinear structures such as scale space approaches with Gaussian derivatives [1], the anisotropic Gauss filtering [2], the fusion of two local line detectors followed by a global Markov random field (MRF) [3], using differential geometric properties of images [4] and using active contour approaches [5]. For the problem of correspondence of curvilinear structures between sets of images, algorithms have been proposed in the literature for applications such as tracking and 3D reconstruction. In the majority of approaches, lines are first detected and then line properties such as orientation, position, width and center lines are used for the matching process [6, 7, 8].

In all of these techniques, a threshold is used to binarize the line detector response prior to matching between the images. In real life noisy video sequences, it is very likely that the required threshold will vary from frame to frame, thus causing a possible loss of the tracked curvilinear structure. Instead of tracking using the binarized response, we propose to use an active contour framework that uses the continuous line detector response to detect and track the curvilinear structures. Our approach has the following features:

1 - Line features are used as external forces with the addition of a sign correction factor that enables arbitrary placement of the initial contour with respect to the desired curvilinear structure (i.e the initial contour can be placed to the right or the left of a vertical linear feature). The active contour model has the advantage that it can operate directly on the continuous detector output which preserves the complete information from the response without the need of binarization.

2- For the tracking part, to cope with large displacement of the curvilinear structures, we propose to use first a motion estimation for the contour placement in the current frame and then deform the estimated location using the same active contour evolution as in the first frame. However, we propose to estimate motion for the endpoints only instead of for all the curvilinear structure points. The motion behind this is that while motion estimation for endpoints can be accurate, it can suffer from the aperture effect for the other points on the curvilinear structure. For points other than the endpoints, we can use the active contour deformation to adjust the contour. This will allow large deformation in the curvilinear structure from frame to frame.

The rest of the paper is organized as follows. Section 2 reviews the classical snake model and proposes the external forces used in the evolution. Section 3 introduces the algorithm for tracking the curvilinear structures based on active contours. A specific biomolecular image application of the proposed tracking algorithm along with quantitative and qualitative tracking results are presented in section 4. Finally, conclusions and future work are presented in section 5.

## 2. ACTIVE CONTOURS: THE SNAKE MODEL

### 2.1. Basic Snake Model

Snakes are parametric active contours that evolve under the influence of a set of internal and external forces [9]. Internal forces are used for regularization purposes to enforce smoothness and continuity on the contour, while external forces are used to help the contour lock onto image features of interest such as edges and lines. Let the contour be represented parametrically as $C(s)$ where $s\epsilon[0,1]$, an energy functional that needs to be minimized is defined as follows [9]:

$$E(C(s)) = \int_0^1 \left( \underbrace{\alpha|C'(s)|^2}_{tension} + \underbrace{\beta|C''(s)|^2}_{rigidity} + E_{ext}(C(s)) \right) ds \quad (1)$$

where $E_{ext}$ is the external snake energy which is application dependent. The classical way to solve for the minimization of the function in (1) is to use the Euler-Lagrange condition based on calculus of variations principles.

Starting with an initial contour location, we embed it into a curve evolution equation by introducing an artificial time parameter $t$:

$$C^t = (I + \tau A)^{-1} C^{t-1} - \tau \nabla E_{ext}(C^{t-1}) \quad (2)$$

where $A$ is a penta-diagonal matrix of snake parameters expressed in terms of the weights $\alpha$ and $\beta$, $I$ is an $N \times N$ unit matrix for a contour represent using $N$ points in the digital space, $C^t$ and $C^{t-1}$ are the contours representations in two successive evolution steps and $\tau$ is the time step used in the discretization.

### 2.2. External Forces for Curvilinear structures

Since we are interested in tracking curvilinear structures in an image $I(x, y)$, we resort to use *ridge* (accordingly *valleys*) features instead of edge features. Ridge features can be detected using a second order derivative of a Gaussian $G''_\sigma(x, y)$. Consider the following external force:

$$\nabla E_{ext} = w_1 (-\nabla L) + w_2\, L\, sign(\langle -\nabla L, \overrightarrow{N} \rangle)\, \overrightarrow{N} \quad (3)$$

where the first term:
$-\nabla L(x, y) = -\nabla \frac{1}{1+|G''_\sigma(x,y)*I(x,y)|^2}$
is a gradient vector field created from the line detector response $|G''_\sigma(x, y) * I(x, y)|$. The purpose of this vector field is to pull the active contour towards the desired curvilinear structure. The second term $L.sign(\langle -\nabla L, \overrightarrow{N} \rangle).\overrightarrow{N}$ is a balloon-based term used to speed convergence of the contour and to help moving the contour in smooth areas (with the sign term inspired by the work of [10]). It is clear from (3) the connection with geodesic active contours evolution equation [11], but here the ridge features are used instead of the edge features.

## 3. TRACKING BY ESTIMATING ENDPOINT MOTION

Active contours used in the literature for tracking are of two major types. The first type, a contour is initialized near the desired region in a frame and allowed to deform until settling on the desired boundary. In the next frame, the contour starts from the position it converged to in the previous frame and deforms again using current frame features [12, 13, 14]. This approach works well as long as region motion is small. In the second category of tracking approaches using active contours, the position of the contour in the new frame is predicted based on the motion between the frames using motion estimation techniques [15, 16]. Thus, the second approach can cope with larger motion between frames.

In order to be able to handle large displacement of the curvilinear structure from frame to frame, we propose to use a motion estimation step to re-initialize the active contour position in the new frame. Applying traditional optical flow techniques to curvilinear structures in noisy image sequences to obtain a dense or even sparse optical flow for the whole frame is likely to fail to extract reliable motion information because of ambiguity that we may face due to the aperture problem. So we resort to a two step approach: first, we estimate the motion of the endpoints and then we adjust the movement of the inner points using the active a contour deformation as in section 2.

In the explanation of the proposed algorithm, we will use the term *tip* to denote one of the two possible ends of the curvilinear structure. Furthermore, the algorithm presented here is capable of tracking multiple structures simultaneously as we will see in the results later. The input to the tracking algorithm at time $t$ is the snake configuration and tip position at time $t - 1$. We will note the tip at a frame $t$ to be $tip(t)$. The tracking algorithm is summarized in the following steps:

1. **Search for the potential new tip position** $tip(t)$ using a searching window $W$ around $tip(t - 1)$. The detection is carried out by applying a line detector on the current frame and thresholding the result using hysterisis thresholding. After thresholding the line detector output, we have a binary map composed of a set of segments that are part of one or more curvilinear structure. We use a test to check for the segments that belong to the curvilinear structure being tracked. The test is based on selecting the segments that are close in terms of Euclidean distance to the detected contour in the previous frame.

2. **Run a test to check if the curvilinear structures is increasing or decreasing in length**. Referring to Fig. 1, we create two vectors $\overrightarrow{w}$ and $\overrightarrow{v}$ where $\overrightarrow{w}$ is the vector connecting the $tip(t)$ to the point labeled $a$ on the figure and $\overrightarrow{v}$ is the vector connecting $tip(t-1)$ and $tip(t)$. if $\overrightarrow{w}.\overrightarrow{v} > 0$, then the curvilinear structure is increasing in length, otherwise it is decreasing or still.

3. a) **Case of increase in length:** As illustrated in Fig. 1.b, we update the snake from frame $t-1$ by adding segment connecting $tip(t-1)$ and $tip(t)$

3. b) **Case of decrease in length:** We first search for the closest point on snake of frame $t-1$ to $tip(t)$. Let's denote the closest point to be $tip'(t)$. Now, as illustrated in Fig. 1.c, we update the snake from frame $t-1$ by cutting out the part from $tip(t-1)$ to $tip'(t)$.

After estimating the position of the two ends of the linear structure in the new frame, we rerun the evolution equation (2) using the updated snake configuration as in step (3) with both ends fixed and with the external forces suggested in section 2.

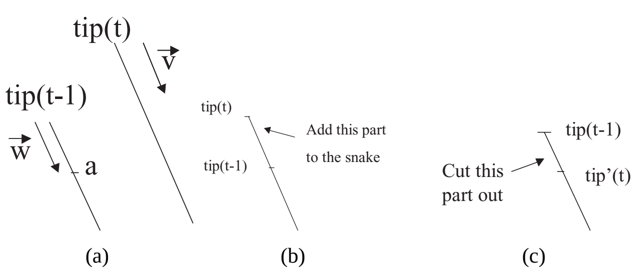


**Fig. 1**. (a) Illustration of the test performed to check if the curvilinear structure is increasing or decreasing in length. (b) and (c) Update of the snake configuration in case of increase and decrease respectively from frame $t-1$ to frame $t$.

## 4. A BIOMOLECULAR IMAGING APPLICATION: TRACKING MICROTUBULES

As an example application of our proposed curvilinear structure tracking algorithm, we tested it on a microtubule videos. Microtubules are very small tubes constituting one of the main components of the cell cytoskeleton [17]. The cytoskeleton is described as the bones and muscles of the cell, thus providing both structure support and capability of movement for the cell. Microtubules are highly dynamic and constantly change their length either by shortening or growing. The dynamic behavior usually occurs at the one end called the tip thereafter. The dynamics of the microtubules are identified in terms of the position of the tip in each video frame. The identification of the tip is currently carried out manually which is a subjective and time consuming task. We ran our proposed algorithm on microtubules to test its performance in tracking the tips. We only consider in this application the movement at one end, the tip so the other end is kept fixed. It is worth noting some unique features about microtubules that make the tracking task challenging:

A) Microtubules appear as tubular structures in the image frames.

B) The tubes undergo large changes in appearance from frame to frame because of growth or shortening at either microtubule ends and the low frame rate (usually a frame is captured each 4 seconds).

In the literature very few papers [18], [19] have addressed the microtubule detection and tracking problems. In [18], a graph searching based technique is used in extracting central axes of microtubules from three dimensional cellular electron tomography images. In this work, only microtubule axes detection is performed without addressing the tracking problem. In [19], microtubule tracking is performed by automatically selecting an initial point on the microtubule and iteratively other points are added using tangent constraints. Once the microtubule is detected, it is tracked in time while constraining the search space in a normal direction around microtubule points. Experimental results are given in [19] but without any quantitative assessment.

### 4.1. Experimental Results

We have tested the proposed tracking algorithm on eight microtubules in four video sequences of an average length 30 frames. We show tracking results on selected frames from these sequences in Fig. 2. The figure shows how the tracker can handle single and multiple microtubule tracking situations and keep the correct microtubule identities through the frames. On the other hand, the tracker fails to track the microtubule in cases of extremely low contrast and when the tip is excessively shortening so as to disappear from the frame. The reader is directed for the full length tracked results at [20] due to page space constraints. Additionally, we evaluate the tracking performance using quantitative measures. Over the eight microtubule tested, the error in estimating the microtubule tip position (from a manual ground truth data) has an average and standard deviation of 2.89 and 1.95 pixels respectively. Biologists consider these error levels to be satisfactory for use in extracting microtubule dynamic parameters such as growth and shortening rates.

## 5. CONCLUSIONS

We have presented in this paper a tracking algorithm for curvilinear structures and applied it to microtubule video stacks. The tracking algorithm is based on active contour using line features as an external force. The experimental results show the usefulness of the approach to handle changes in shape and large amount of motion. Both qual-

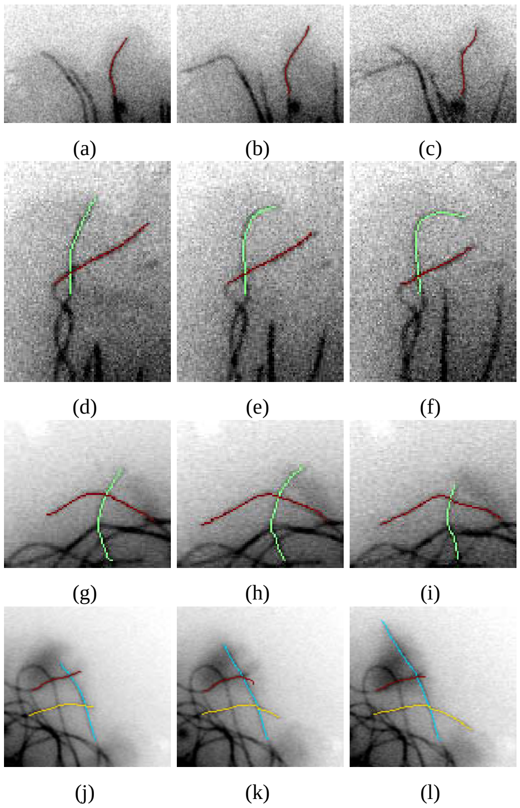

**Fig. 2**. Some example tracking results for microtublues showing the capability of the tracker to track highly flexible structures in noisy conditions. (a)-(c) frames 0,7,30 from sequence 1, (d)-(f) frames 0, 5, 13 from sequence 2, (g) -(i) frames 4, 12 , 26 from sequence 3 and (j)-(l) frames 0, 7, 17 from sequence 4. Subfigure (j) shows a case of failure of tracking the tip part of the "red" tube because of very low contrast.

itative and quantitative tracking results have been shown for the case of one and multiple microtubules. More research is needed to handle the cases when curvilinear cross each other momentarily and when they disappear for some frames due to excessive decrease in length.

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