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Multi-feature gradient vector flow snakes for adaptive segmentation of the ultrasound images of breast cancer

Annupan Rodtook [a], Stanislav S. Makhanov [b,*]

[a] Department of Computer Science, Ramkhamhaeng University, Bangkok 10240, Thailand
[b] School of Information and Computer Technology, Sirindhorn International Institute of Technology, Thammasat University, Pathum Thani 12000, Thailand

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ABSTRACT

Segmentation of ultrasound (US) images of breast cancer is one of the most challenging problems of the modern medical image processing. A number of popular codes for US segmentation are based on a generalized gradient vector flow (GGVF) method proposed by Xu and Prince. The GGVF equations include a smoothing term (diffusion) applied to regions of small gradients of the edge map and a stopping term to fix and extend large gradients appearing at the boundary of the object.

The paper proposes two new directions. The first component is diffusion as a polynomial function of the intensity of the edge map. The second component is the orientation score of the vector field. The new features are integrated into the GGVF equations in the smoothing and the stopping term.

The algorithms, having been tested by a set of ground truth images, show that the proposed techniques lead to a better convergence and better segmentation accuracy with the reference to conventional GGVF snakes. The adaptive multi-feature snake does not require any hand-tuning. However, it is as efficient as the standard GGVF with the parameters selected by the "brutal force approach". Finally, proposed approach has been tested against recent modifications of GGVF, i.e. the Poisson gradient vector flow, the mixed noise vector flow and the convolution vector flow. The numerical tests employing 195 synthetic and 48 real ultrasound images show a tangible improvement in the accuracy of segmentation.

1. Introduction

The accuracy of the computer based diagnostics of the ultrasound images of breast is still not sufficient especially in early stages when the cancers are very subtle and vary in appearance. Moreover, it is often difficult to separate the tumor from the background even when its existence is evident. Therefore, segmentation of tumors is one of the most important problems in the computer aided US diagnostics of breast cancer.

Among the most promising techniques for extraction of complex objects from digital images are active contours or snakes, originally introduced by Kass et al. [1]. Since the seminal work of Kass and colleagues, techniques based on active contours have been applied to many object extraction tasks with a different degree of success.

In particular, snakes have been used to locate the objects in various applications of medical image processing such as segmentation of abnormalities in the images of the human heart, liver, brain, breast [2–10]. The main drawback of the method is that the noise and small objects may attract the snake to a local energy minimum, which does not correspond to the actual boundary. Therefore, to reach the desired boundary, the initial contour should be initialized close to the object. The most important component of the snake based segmentation is an external force which pushes the snake towards the object. This force is usually derived from the gradient of the image gray level. Therefore, in order to enhance the effect of the external force the gradient created nearby the boundary must be extended so that the snake "feels" the object even if it is initialized far from it.

A popular solution is the balloon snake where such a force is generated artificially. This works for both contracting and growing snakes (balloons or artificially inflated contours) proposed in [11]. The distance snakes [12] exploit a similar idea. The external force is constructed as the negative of the external energy gradient, which is the distance from each point to its closest edge points in the image. Consequently, the initial contour can be located far away from the desired boundary if there are no spurious edges along the way. Furthermore, many variations of this idea such as the "stop and go" snakes [13], multi-direction snakes [14], gravitation force snakes [15], watershed-balloon snakes [16], balloon snakes with nonlinear filtering [17] have been introduced and analyzed. The image force is modified or altered to increase the capture range and decrease the sensitivity to a possible noise, shadows and (in case of the medical images) obstructing structures and tissues.

* Corresponding author.
E-mail address: makhanov@siit.tu.ac.th (S.S. Makhanov).

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Another group of methods is based on minimization of the energy subject to a certain conditions improving the convergence and accuracy. Sectored snakes [18] deform the contour subject to constraints derived from a priori knowledge of the object shape, extracted from the training set of images. Fourier type descriptors have been used in [19] to evolve the curve to a prescribed shape defined by a template. The prior information is introduced through a set of invariants (translation, rotation and scaling) computed using the Fourier Transform. Furthermore, the force includes not only the edge based features but region based features as well. For instance, the homogeneity of the enclosed region [20,21]. In [22] region-based image features are combined with the edge-based features incorporated in the external forces.

Starting from multiple seeds, [22] performs segmentation of the entire image by iterative boundary deformation and region merging iteratively.

The so-called T-snakes proposed in [23] and their improvements such as the dual T-snakes [24] based on iterative re-parameterization of the original contour are able to make the use of the self loops. However, the approach allows only "rigid" deformations limited by the superimposed "simplicial grid". An intrinsic internal force that does not depend on contour parameterization based on regularized contour curvature profile has been proposed in [25,26].

A competing approach called the level set method (LSM) [27] is based on the ideas proposed by Osher and Sethian [28] to use a model of propagating liquid interfaces with curvature-dependent speeds. The LSM combined with the contour energy minimization resulted in a variety of the so-called geodesic deformable models [29–32]. However, the LSM makes it difficult to impose arbitrary geometric or topological constraints on the evolving contour via the higher dimensional hyper surface. Besides, the level set models may generate shapes having inconsistent topology with respect to the actual object, when applied to noisy images characterized by large boundary gaps [33] and non-closed curves [34].

Another group of competing approaches includes region based models aiming to smooth the image within the homogeneous regions but not across the boundaries of such regions. One of the most popular and widely studied is the Mumford and Shah model [79]. The original Mumford–Shah functional consists of a fidelity term, forcing the solution to be as close as possible to the given image, a smoothing term forcing the solution to be as smooth as possible everywhere except the image discontinuities and the geometric term, forcing the total length of the edges to be as short as possible. A variety of the Mumford–Shah model has been proposed and analyzed (see a survey [80]). One of the most significant developments is the Chan–Vese model [81] which is a level set implementation of the piecewise constant case of the Mumford–Shah model. Recent combinations of the Mumford–Shah techniques and active contours include active contours without edges [82], splitting active contours [83] and Mumford–Shah shape-prior active contours [84].

Rochery et al. propose a parametric model for higher-order active contours, in particular, quadratic snakes, for extraction of linear structures like roads [35]. The idea is to use a quadratic formulation of the contour's geometric energy to encourage anti-parallel tangents on opposite sides of a road and parallel tangents along the same side of a road. These priors increase the final contour's robustness to partial occlusions, decrease the likelihood of false detections in regions not shaped like roads, and help to prevent self-looping.

Further improvements lie along the lines of processing the underlying vector field rather than modifying the snake model itself. A number of popular codes are based on a gradient vector flow (GVF) method proposed by Xu and Prince [36,37]. A "raw" gradient vector field derived from the image edges is replaced by a vector field which minimizes a certain variational functional. The functional is designed to extend the large gradients far from the boundary, smooth the noise and speckles while keeping gradients attached to strong edges.

The generalized gradient vector flow field (GGVF) [38] extends the GVF method by introducing non-uniform diffusion. The GGVF is defined as a steady state solution of a system of parabolic equations with the elliptic terms and the source term similar to the GVF model. However, the GGVF employs space-dependent diffusion which provides better segmentation accuracy and a larger capture range. Some variations of these ideas are the multidirectional GGVF based on a special algorithm to evaluate the gradients and the diffusion coefficients [14] and the non-linear diffusion method presented in [39].

Numerous research papers apply the GGVF based active contours to medical images. The examples are multi-direction snakes: skin cancer images [14], topology-adaptive snakes: MR brain images and CT scans[23], gravitational force snakes: a variety of medical and non-medical images [15], narrow-band snakes: MRI and CT scan images of lungs [40], distance snake, GVF snake, balloon snake, "area and length" snakes, geodesic snakes, constrained snakes and level set method: MRI, CT and US images of brain, liver, kidney [32], region-competition snakes (originally [22]): CT scan slices of arteries [41], sectored snakes: abdominal CT scans[5], parametric snakes: US of breast masses [42], 3D-snakes: US breast cancer images [42,43], GVF snakes with edge map pre-processing: US of the kidney tumors [9], GVF snakes combined with the region growing and the median filter: US breast tumors [10], sketch-snakes: chest X-ray images [43], combination of snakes and active shape models: US of the human heart [44], the so-called early-vision and the discrete-snake model: a variety of the US images [47], multi-resolution snake: echographic and echobrachial images [48], GGVF snakes combined with a continuous force field analysis: breast tumor US images [49].

The success of such segmentations critically depends on preprocessing. As a matter of fact, it is often more important than selecting and tuning the active contour. The Gaussian, mean and median filters [50], Gabor filters [47] and speckle noise filters [50–53] are among the most popular for the US imagery. A fusion of the median and the Wiener filter combined with a contrast adjustment technique and the Frost speckle filter [52] is applied in [54]. A tree-structured nonlinear filter and special types of wavelet transforms has been proposed for transrectal ultrasound [55]. The active contour is used by the segmentation module. A comparison between the segmented image with and without the preprocessing shows that this module provides an improvement in the accuracy of the boundary detection. A combination of filtering, edge map and initialization by a human operator [10] employs an iterative truncated median filter to reduce the speckle noise. In [56] the speckle noise is suppressed by anisotropic diffusion filter [57] and a stick filter [58].

More often than not, the preprocessing is not a single step but a well arranged sequence of operations including (but not limited to) filtering, morphological transformations and edge detection procedures specific for the particular type of medical imagery. A combination of region growing and median filtering is proposed for the GGVF snakes in [10]. A single run of the anisotropic diffusion filter (non-linear filter [59]) is proposed for the multi direction snake [14]. Non-linear filters applied to the GVF vector field (rather than to the original image) are discussed in [17]. A curvature diffusion filter [60] is applied with the LSM to sonographic images of breast. An interactive medical image segmentation (sketch snakes) is introduced in [45,61]. Some preprocessing operations such as the edge detection can be also controlled interactively by a human operator. A preprocessing for density-based segmentation [62] employs histogram adjustment, noise reduction using an iterative dilation [63] and a median filtering to suppress the spike-like noise.