Tracking Left Ventricular Wall Motion using Active Contour Model: PR-Greedy Algorithm

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Abstract. The active contour model (ACM) Snakes permits to simultaneously solve, in constrained cases, both the segmentation and tracking problems and has been proposed by [Kass et al (1987)]. The aim of this work is to propose a particular ACM formulation to track and analyze left ventricular (LV) endocardial wall motion from color kinesis (CK) echocardiography images [Murta (1998)]. A new approach called PR-Greedy algorithm is presented.

Keywords: Active Contour Model, Cardiac Left Ventricular Motion, Color Kinesis, Deformable Contour, Greedy Algorithm, Image Segmentation, Snakes, Splines.

1 Introduction

Two-dimensional echocardiography is widely used for the evaluation of regional LV function because of its ability to depict endocardial excursion and wall thickening in real time. In view of qualitative improvements in medical diagnoses, a wide variety of techniques have been developed. Because it is often difficult to precisely define the endocardial and epicardial boundaries, these methods remain subjective and impractical for routine clinical use.

Unfortunately, there are significant problems with many of the approaches proposed by the computer vision community for tracking cardiac motion across several imaging modalities that affect their ability to accurately estimate wall motion. Primary objections to these approaches include the inability to estimate point-wise motion, the lack of tracking specific points on the wall over time and the inherent problems of measuring the motion of a 3D spatially deformable object from 2D projections.

CK is a new technique based on acoustic quantification developed to facilitate the evaluation of regional wall motion; it tracks the motion of the endocardium in real time throughout systole which results in high quality color-encoded images reflecting the magnitude and timing of endocardial motion [Lang et al. (1996)]. Figure 1 shows a CK image from Hospital das Clínicas de Ribeirão Preto (HCRP – USP). Although CK direct represents the LV wall motion, it does not clearly define the LV boundaries, as there are needed for most diagnoses parameters in cardiac evaluation.

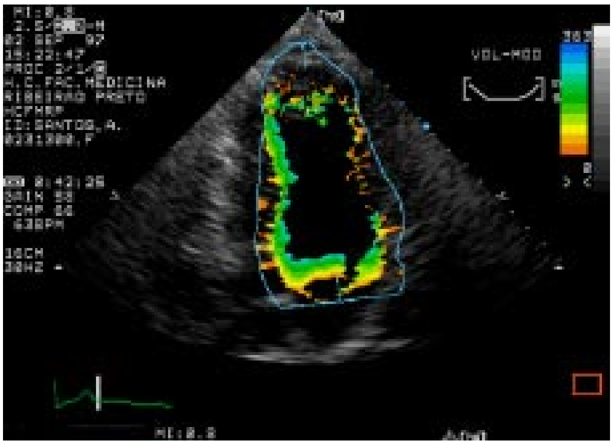

Fig. 1 – LV 4-chambers ultrasound image from Sonos HP 2500 echocardiography (HCRP - USP, Brazil).

To enhance these boundaries an active contour model can be used. Snakes [Kass et al. (1987)] is a physically based description of the contours to constrain the solution of movement. It is an energy-minimizing spline guided by external constraint forces and influenced by image forces that pull it toward features such as lines and edges. They lock onto nearby edges, localizing them accurately. Snakes provide a unified account of a number of visual problems, including detection of edges, lines and subjective contours, motion tracking and stereo matching.

As we will be shown further, the original Snakes formulation is not suitable to be applied under the circumstances presented by CK images. Therefore, a new approach to active contour model here called PR-Greedy is proposed.

2 Basic Snake Behavior

A Snake can be parametrically represented by $\mathrm{v}(s)=(x(s), y(s))$ and its energy functional can be written as

$$E = \int_0^1 E_{int}(\mathrm{v(s)})ds + \int_0^1 E_{image}(\mathrm{v(s)})ds + \int_0^1 E_{ext}(\mathrm{v(s)})ds \quad (1)$$

where E_{int} represents the internal energy of the spline due to bending, E_{image} gives rise to the image forces and E_{ext} gives rise to the external constraint forces.

The spline energy is composed of a first order term controlled by $\alpha(s)$ and a second term controlled by $\beta(s)$. Therefore, the internal spline energy can be written

$$E_{int} = \frac{\left(\alpha(s)\left|\mathrm{v_s}(s)\right|^2 + \beta(s)\left|\mathrm{v_{ss}}(s)\right|^2\right)}{2} \quad (2)$$

The generic total image energy can be expressed as a weighted combination of the three energy functionals

$$E_{image} = w_{line}E_{line} + w_{edge}E_{edge} + w_{term}E_{term} \quad (3)$$

The simplest useful image functional is the image intensity. The termination functional can be implemented with a gradient direction calculus in a slightly smoothed version of the image [Kass et al. (1987)]. A variety of functionals can be used to improve subjective contours detection [Williams – Shah (1992), Leymarie – Levine (1993)]. Snake instability and point clustering have also been addressed [Amini et al. (1988)].

The third energy term E_{ext} relates to external forces and it is defined to improve special features for a particular tracking. This term is responsible to position the Snake nearby the object and to improve semi-automatic action.

The Kass procedure is an $O(n)$ iterative technique which uses sparse matrix methods [Kass et al. (1987)]. Each iteration effectively takes implicit Euler steps with respect to the internal energy and explicit Euler steps with respect to the image and external constraint energy. Since the internal energy is adjusted implicitly, the procedure remains stable in the presence of very large internal forces.

Williams & Shah [Williams – Shah (1992)] have proposed a particular discrete approach to improve the Kass formulation. As their mathematical tools and background differ from the ACM by Kass, new complexities have been arisen. Their so called Greedy algorithm uses curvature estimation without differential equations complexity penalty and allows the inclusion of hard constraints described by [Amini et al. (1988)]. Greedy is $O(nm)$ for a contour having n points which are allowed to move to any other location in a neighborhood of size m. While the algorithm is no guaranteed to give a global minimum, the experimental results have been compared to other methods [Williams – Shah (1992)].

4 A New Algorithm: PR-Greedy

The Greedy algorithm was chosen as a start point to track boundaries in CK images. At least two majors new difficulties were found when using this algorithm in CK images: corner with binary value representation and poor formulation for image forces in CK images. PR-Greedy presents improvements in these directions.

The quantity being minimized in this case is

$$E = \int_0^1 \alpha(s)E_{cont}(\mathrm{v(s)})ds + \int_0^1 \beta(s)E_{curv}(\mathrm{v(s)})ds + \\ + \int_0^1 \gamma(s)E_{image}(\mathrm{v(s)})ds \quad (4)$$

where E_{cont} is a first-order continuity term that measures distance between curve points, E_{curv} is a second-order term that measures curvature, E_{image} retains the image energy and $\alpha(s)$, $\beta(s)$ and $\gamma(s)$ are the weight-parameters.

A new functional energy E_{cont} based on 2 neighbors points using global mean evaluation is proposed as formulated in Eq. 5:

$$E_{cont} = \left| d(\mathbf{v}_i, \mathbf{v}_{i-1}) + d(\mathbf{v}_i, \mathbf{v}_{i+1}) + \\ - d(\mathbf{v}_i^*, \mathbf{v}_{i-1}) - d(\mathbf{v}_i^*, \mathbf{v}_{i+1}) \right| \quad (5)$$

where $\mathbf{v}_i$ represents the i-point from $\mathrm{v}(s)$ curve, $\mathbf{v}_i^*$ represents a possible location for the i-point and d is the Euclidian distance. This functional presents better stability than Greedy due that points remain stationary when no others forces are acting. Therefore, the star-phenomena is eliminated in this formulation.

The second term is curvature and a list of formulations is presented by [Williams – Shah (1992)]. The best choice is

$$E_{curv} = \left|\mathbf{v}_i - \mathbf{v}_{i+1}\right|^2 . \quad (6)$$

Although there are other formulation more cost effective, Eq. 6 is chosen for pointwise curvature estimation.

The third term is a gradient magnitude. The normalization suggested [Kass et al. (1987)] considers the neighborhood of the pixel in question using a local normalization. The original functional searches dark colors and depreciate light colors or vice-versa, and it has been known as a good formulation for gray scale images. Since CK images uses RGB code, a new functional based on a target-color philosophy in 3D space has to be formulated as follows:

$$E_{image} = d\left(\mathbf{v}_i.color, \mathbf{v}_i^*.color\right). \tag{7}$$

The PR-Greedy algorithm is presented in Fig. 2.

```
Index arithmetic is modulo n.
Initialize αi, βi and γi to 1 for all i.
Do
   /*loop to move points to new locations */
   For all i points in contour
      Emin = INFINITY
      For all points in neighborhood  ii x jj
         E = αi Econt(i,ii,jj) +βi Ecurv (ii,jj)+ γi Eimage(ii,jj)
         If E < Emin then
            /*save energy and location*/
            Emin = E
            MinimalLocation = (ii,jj)
      If  MinimalLocation ≠ current location
         Move point ui to MinimalLocation
         Increment points moved counter
   /*are corners allowed in next iteraction?*/
   For all i points in contour
      ci = | ui/|ui| − ui+1/|ui+1| |^2
   For all i points in contour
      If (ci > ci-1) and (ci > ci+1) and (ci > threshold1)
      and mag(ui) > threshold2 then
         Weight adjustment
until movement is too much small
```

$$c_i = \left| \frac{u_i}{|u_i|} - \frac{u_{i+1}}{|u_{i+1}|} \right|^2$$

Fig. 2 – PR-Greedy Pseudo-Code.

6 PR-Greedy Algorithm Results

In order to validate PR-Greedy algorithm we have developed a PC-based software. Early tests with a small set of images provided the results herein presented. The software development base consist of Borland Delphi environment for Windows 9x platform.

CK images have been acquired from a HP 2500 Sonos Echocardiograph unit using a HP MO Driver. The file format TIFF HP Extended is the original format from HP with patient data and image sequence encapsulation. At this stage we are converting TIFF HP Extended to Windows TIF and then to Windows BMP 32 bits format without any quality loss.

Preliminary tests showed that PR-Greedy parameters have their best relation as

$$\beta = 25(\alpha - 0{,}01) + 0{,}05 \tag{8}$$

where α is the first term weight (continuity) and β is the second term weight (curvature). This result was found in 4D-space [α, β, time, focus radius] with 5% error for $\alpha = \beta$ = [0,3] $\in \mathbf{Q}$. Successful γ parameter range is [0,3]$\in \mathbf{Q}$.

7 Conclusion

A new active contour model called PR-Greedy is presented and has been designed to work properly with CK images. Improved functionals for continuity and image energies have also risen from this work.

We believe that there is a connection with CK images and deformable active contour model. CK images need fast boundary reconstruction and local energy minimizing systems like ACM can offer an attractive method for doing so. Our results presents a new trend in this direction. Further tests and developments will improve the PR-Greedy algorithm specially by promoting a better description for continuity and curvature parameters.

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