Using Motion Estimation and Regularization for Recovering the 3D Shape of the Beating Left Ventricle from Echographic Images

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Abstract

We describe efficient and robust deformable model based techniques for three dimensional reconstruction of the left ventricle from ultrasound images. Motion estimation is used to compute a first estimation of the ventricular shape.This estimation is then refined with 3D deformable surfaces. Results are presented demonstrating tracking on various echographic sequences.

1. Introduction

Quantitative analysis of the 3D shape of the left ventricle during the beat provides additional valuable clinical information on the cardiac pumping function. In the past, simplified geometrical models (ellipsoids) of the left ventricle have been used to assess the pumping function from a small number of views. Unfortunately, they do not allow an accurate assessment of the pumping function. With the advent of rotating transducers [5], the entire cardiac volume can be scanned very tightly and it is now conceivable to recover the 3D shape of the ventricle from these data. However, they are significant problems for tracking 3D cardiac motion over time. The main difficulty is to detect the ventricular border in each view: due to the low signal to noise ratio and to drop outs, classical edge detectors fail to recover the ventricular border. These scattered and noisy data must then be integrated to recover the 3D shape of the LV. Deformable models [4] are an effective mean to achieve this task: within this framework, objects are modeled as elastically deformable bodies subject to *physical constraints*. Internal forces are used to integrate smoothness constraints while external forces act as attracting forces towards the image data. 3D deformable surfaces have been applied successfully to the recovery of the 3D shape of the ventricle[3, 6]. In [6], Acoustic Quantification is used to detect the border between endocardial tissue and blood automatically. Then, deformable shells models are used to recover the LV shape. In [3], Coppini and his collegues use a surface-plus-string system. The left ventricular border is detected using neural networks. The data set acts on the surface as a set of radial springs joining each 3D boundary point to the surface itself. The internal energy is classically defined as $E_{int} = \int_{\Sigma}(2H^2 - K)ds$ where H and K are the mean and the gaussian curvature of the surface Σ.

However, both approaches rely on a prior segmentation of each scan view to detect the ventricular border. This task is known to be very dependent on the initial settings of the echograph and on the threshold values used in the segmentation process. The above considerations led us to develop a fully automated system based on a tracking approach for recovering the LV surface from a set of apical views. This way, the segmentation task is made easier because the photometric aspect of the ventricular wall at a given time instant is used to predict and to search for the ventricular wall in a small area in the next frame.

2. Overview of the system

We hereby present briefly the system we have developed for 4D acquisition using a trans-thoracic approach [5]. The system consists of a probe rotating around its axis. The probe is controlled by an electronic device triggered by the ECG signal taken directly from the patient. For each rotation of the probe, an entire heart contraction is recorded at a 25 frames/sec rate. The acquisition product is a database which can be represented in a matrix format. Its size is 8×9 because we only acquire images between end diastolic and end systolic (8 images) and the probe rotation is 20 degrees.

Fig. 2 summarizes the software developed for three dimensional reconstruction of the beating ventricle through the cardiac cycle. To begin with, the ventricle is manually traced by the cardiologist at the first time instant in each scan plane. Then, our algorithm operates in a loop following two major steps: (i) the ventricle is automatically tracked between time instant t and $t+1$ in each scan plane using correlation based methods and motion based methods.

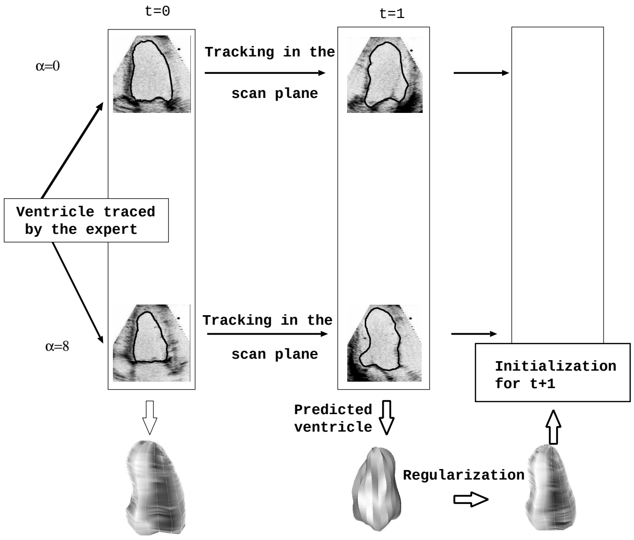

Figure 1. Overview of the system

This provides us with a good prediction of the 3D shape of the ventricle at $t+1$; (ii) 3D deformable models are used to regularize the recovered ventricle and to remove possible tracking errors.

The tracking stage along with the reconstruction stage are described into details in section 3 and 4. Finally, we show in section 5 experimental results that demonstrate the validity of our approach.

3. Tracking the ventricular border in 2D

The tracking algorithm has been previously described in [1]. We only summarize in this section the outlines of our method.

Following previous works on deformable structures [2] we use a hierarchical algorithm; we first compute a global estimation of the ventricular deformation. Then, we use a fine tuning deformation to adjust the details. The global estimation is based on a parametric motion model with a small number of parameters (4, 5 or 6). These parameters are estimated in a robust way from the velocity field computed at each point of the contour. From this estimation, active contour models are used to detect the ventricular wall. Once tracking has been achieved in each scan plane between time t and $t+1$, a rough estimate of the 3D shape of the ventricle can be computed. However, possible tracking errors create reconstruction artifacts on the surface (Fig. 3.a). 3D regularization is then achieved to recover the shape of the ventricle.

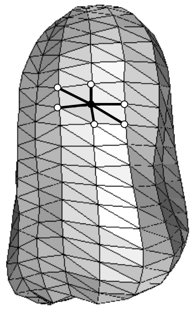

Figure 2. The triangulated surface of the ventricle and the neighborhood of a point

4. Tracking the ventricle in 3D

At this point we need a few definitions. We represent the polyhedral surface of the ventricle as a pair of lists $S = \{V, F\}$ a list of n vertices V and a list of triangular faces F. The neighborhood of a vertex v_i is a set i^* of indices of vertices. The two points which are lying on the probe axis have 2×9 neighbors (2 in each scan plane) whereas the other points have 6 neighbors (see Fig. 2).

The method we use for 3D reconstruction of the ventricle from the initial guess V originates in the widely used deformable models proposed in [4]. The ventricle is therefore defined as the set of vertices V which minimizes the energy term

$$E = \sum_{i=1}^{n} E_{internal}(v_i) + \lambda E_{external}(v_i)$$

Classically, generalized spline functionals of the first and second order are used as smoothness measure. However, these terms are highly non linear. That is the reason why we use a simple first order energy:

$$E_{internal}(v_i) = \sum_{j \in i^*} |v_i - v_j|$$

This terms minimizes the length of the mesh. Consequently, reconstruction artifacts due to tracking errors will be removed.

The external term is the one classically used in active contour models. Each vertex v_i is submitted to the force field created by the image gradient:

$$E_{external}(v_i) = -|\nabla I_{im(i)}(v_i)|$$

where $I_{im(i)}$ is the intensity image the point v_i belongs to.

In addition, we modify the external term to impose prior information on the ventricular wall. Indeed, the ventricular cavity is filled with blood and appears as a relatively homogeneous clear region in the images. On the contrary, tissues appear as dark regions. Hence, the image gradient at each point of the ventricular wall points outwards. This constraint can be expressed as $n(v).\nabla I(v) > 0$ where $n(v)$ is the normal to the curve at each point v.

The new external energy is therefore defined as:

$$E_{external}(v_i) = \begin{cases} -|\nabla I_{im(i)}(v_i)| \; if \; n(v).\nabla I(v) > 0 \\ 0 \; otherwise \end{cases}$$

This term generally prevents the surface to be attracted by other structures than the ventricular wall.

Note that minimization of E is achieved by using a semi implicit numerical scheme inspired from the one described in [4].

5. Experimental results

Our experiments have been carried out with an echograph biosound AU3. In Fig. 3, an example of the reconstructed surface is shown: Fig. 3.a exhibits the predicted ventricle obtained after the tracking stage whereas Fig. 3.b shows the regularized shape. To better understand the interest of 3D regularization, we superimposed the non-regularized (in black) and the regularized (in grey) ventricle in Fig. 3.c. This figure proves that nearly all artifacts created by drop-outs are removed by the regularization process. Fig. 5 shows an entire temporal sequence from end-diastolic to end-systolic.

We also show in Fig. 4 the ventricular wall in one of the scan plane from ED to ES. This figure proves that the regularization process allows tracking errors to be corrected while keeping a good localization accuracy. Finally, Fig. 6 shows the ventricular volume computed over time.

6. Conclusion

We have proposed a robust method for 3D recovery of the shape of the left ventricle without learning stage. We obtain very promising results. We now want to investigate the localization accuracy of our algorithm. To do this, we want to compare the computed ventricular volume with the one obtained from the ventricular contours traced by an expert on the matrix data base.

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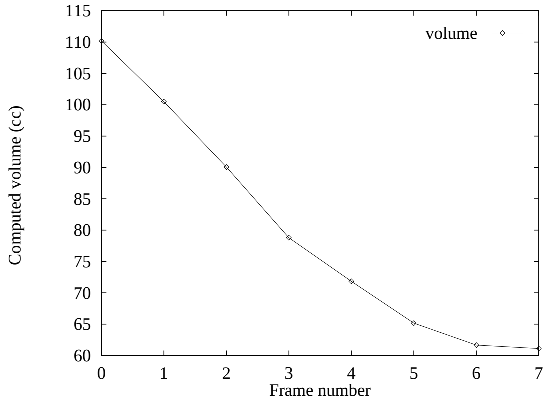

Figure 6. LV volume time curve from ED to ES.

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Figure 3. Regularization of the predicted ventricle: (a) the predicted ventricle (b) the regularized ventricle (c) superimposition of the non smoothed (in black) and the smoothed ventricle (in grey).

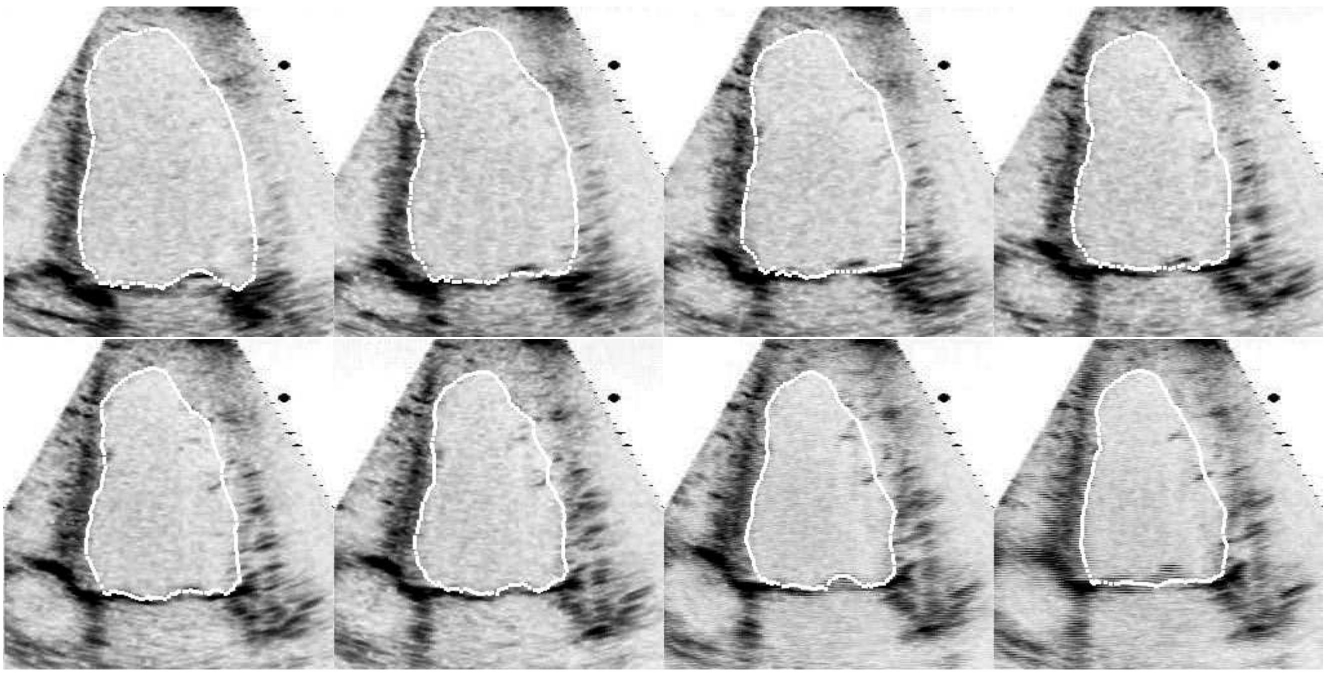

Figure 4. The ventricular wall detected in a given scan plane from ED to ES.

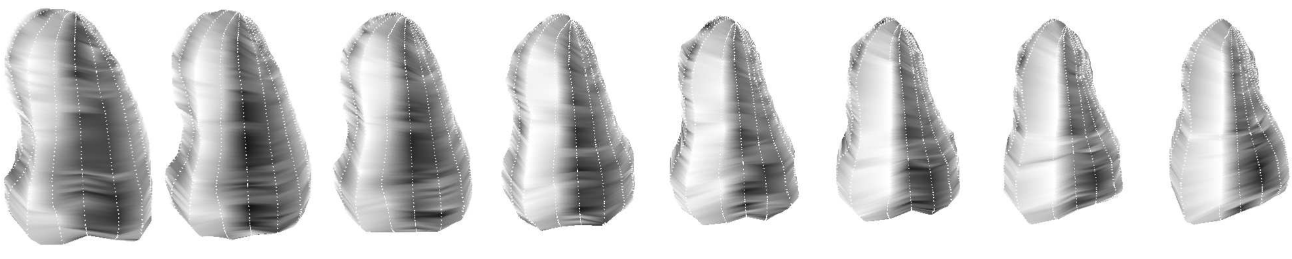

Figure 5. Snapshots of the reconstructed beating ventricle from ED to ES.