Curvature-based Diagram Description of Deforming Contour and Its Application to X-ray Cardiac Image Diagnosis

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This paper proposes a method to describe left-ventricular (LV) motion in X-ray cardiac (heart) images using a curvature-based process diagram. Based on this diagram, shape dynamics can be described as graph patterns to enable an easy interpretation for medical diagnosis. We take curvatures of two regional contours of X-ray heart image as characteristics of the shape, because these parts are deeply related to heart disease. Plotting these curvatures in the diagram during endocardium motion, we obtain graph pattern. In this diagram, every point location corresponds to LV contour shape, and the pattern corresponds to its motion. So that, even though LV shapes differ from each person individually, we obtain same patterns if their motions are same. We applied the method to real X-ray images and compared between normal and abnormal left-ventricular motions. The results promises the possibility of automated diagnosis from these diagram patterns.

KEYWORDS: Medical image diagnosis, X-ray cardiac image, Computer vision, Deformable shape analysis, Contour shape analysis

1 Introduction

In this paper, we consider a method to describe the change of a non-rigid contour shape, for the application of medical diagnosis with X-ray time-series images of heart (cardiac images). In medical diagnosis, the role and importance of imaging technology has been rapidly growing up and its progress is increasing in recent years. In order to extract efficiently the required information from huge image data and to utilize for diagnosis, the automatic recognition becomes important and necessary. Many researches have been devoted into the motion analysis of the dynamic heart images. Especially the motion analysis of left ventricle has been obtained much attention because the detection of some local motion feature of the heart wall may lead to discover the existence of a disease. Since, in the motion image of the patient's heart with a disease, a difference from that of a normal heart appears in the local form and the motion of a specific part portion, develop went of a method to describe the image partial motions will be important. Here, we propose a method called *diagram* which describes a motion of the image contour portion which would be closely related to a heart disease.

The conventional approaches reported in [1] and [2] employed a method of approximating the overall contour of a left ventricle image with some analytic forms, and checked the change of their parameters. However, they aimed at only detecting some unusualness and have not made reference about how and what amount the contour shape moved.

The diagram proposed in this paper is a graph of 2-dimensional (κ_1, κ_2) trajectory in a plane spanned with two curvatures of the heart contour at the interesting points related to the disease.

We consider the trajectory within one expansion-contraction cycle of heart beat as a pattern, and compare with the normal pattern of the trajectory. It will be helpful for visual qualitative diagnosis of the patient heart condition. Each point along a diagram corresponds to the shape of heart and the trajectory of a diagram shows the shape change.

A non-rigid body object having smooth surface is difficult to extract its characteristic image features. For such the surface, curvature is an effective one. Here, we employ the method of Leyton's [3] as a shape description method of the image motion of a smooth contour. Leyton proposed the *process grammar* which used the curvature of contour shape for its classification and matching, and also proposed the *process diagram* to express the relation between different shapes.

We observe the curvature change of the contour of heart shape, and develop its diagram as a description of the dynamical state changes of the contour shape. We applied this description to real medical X-ray images of heart.

Hereafter, Chapter 2 describes the contour shape extraction from a series of X-ray heart images. Chapter 3 explains the shape description method with the process-grammar. The application of the Leyton's process grammar to describe the motion of the left ventricle in X-ray heart image is shown in Chapter 4. Chapter 5 shows the experimental results of the application of the proposed method to a diagnosis of the real X-ray images.

2 Extraction of a smooth contour from X-ray image sequence

Firstly, we describe a method which extracts the contour of the left ventricle from a series of X-ray images of a heart. In the medical image, usually contours of a target shape are consisting with complex curves with poor contrasts, and has large differences between individuals. So, it is difficult to extract the contour of an object domain correctly. Therefore, it is usual for doctors to trace and extract manually the contour of an interested region (ROI, Region Of Interest) with a pen, etc. [4]. However, processing by the human needs a labor and may produce operator's individual differences. Moreover, there is no reproducibility and there is also a problem that it will not be convenient to use for subsequent computer analysis. Then, many works has been reported to perform this process automatically [5]. In our research, to extract the image contour, we employed one of such the method by using the dynamic contour named the snake [6] [7].

2.1 Extraction of a left ventricle domain using snake

In the contour extraction by dynamic contour snake, the initial closed curve roughly given on the image is brought close gradually to a true object contour. The contour curve is moved so that the energy function defined from the information on the image gray values on the curve and its own shape is minimized. In this paper, the contour of a left ventricle was extracted from the image sequence using the energy function of (1).

$$E[C] = \oint_C \left\{ \frac{1}{2} (\alpha |\mathbf{r}_s|^2 + \beta |\mathbf{r}_{ss}|^2) - \lambda |\vec{\nabla} I|^2 + \gamma |\mathbf{r}_t|^2 \right\} ds \quad (1)$$

where

$$\begin{aligned} C &: \text{Contour} \\ \mathbf{r}(s, t) &= (x(s, t), y(s, t)): \text{Position of the point on the contour} \\ s &: \text{Arc length measured from a certain point} \\ t &: \text{Time (number of calculation steps)} \\ I(x, y) &: \text{Image gray value at position } (x, y) \end{aligned} \quad (2)$$

This energy is defined on a curve. We change the curve shape next by next so that whole energy becomes the minimum. The first term expresses the total arc length. When α is positive, making this term small corresponds to shortening the total arc length of the contour. The second term relates to the curve curvature. When β is positive, making this small corresponds to smoothening the contour. The third term evaluates the gradient of the gray-level along with the curve. When λ is positive, making this term small will make the curve pass through the place of large gray-level gradients.

In this research, in order to treat the series image of the expansion-contraction cycle of the heart, it is desirable that the contour changing smoothly between adjacent time frames is obtained. Then, a term which maintains the continuity of the contour between subsequent image frames was added to the energy function. The forth term in (1) make reference of the adjoined image within a series in the minimization of the energy function (Fig. 1).

The contour of a left ventricle extracted from a series of X-ray images using this energy function (1) is shown in Fig. 2. The parameters given for calculation of the energy function for this image were; $\alpha = 0.1$, $\beta = 0.2$, $\lambda = 0.05$, and $\gamma = 0.1$.

Fig. 1 Contour extraction by referring the subsequent images

Fig. 2 An example of extracted contour from a heart X-ray image

Fig. 3 Curvature extremum and its label. The left figure is the plot of curvature of right figure along with the arc length

3 Process grammar

This chapter explains the process grammar proposed by Leyton [3]. It will be used as the basis of the method of describing a contour. His method first makes labeling for curvature extremum points on a non-rigid contour which does not have clear feature point. Then, the transitional change of the contour shape is described with the change of the labeling. When the curvature of a contour is plotted as a function of arc length, there are four kinds of its extrema as shown in Fig. 3. For those curvature extrema, the next labelings were given.

- M^+ : positive local maximum (protrusion)
- m^+ : positive local minimum (squashing)
- m^- : negative local minimum (indentation)
- M^- : negative local maximum (internal resistance)

A contour shape is classified into the classes as shown in Fig. 4 according to the number of labels.

Leyton tied up the classified contours with the concept of the process. Here, the process is a rewriting rule of the labels which describes the change of object contours.

Examples of possible processes are listed up in Fig. 5. With these processes a contour changes its shape into another one just like as shown in Fig. 6. The process diagram is the hierarchical description of 'possible' transformation between contours which were tied up with the process. Figure 7 shows the process diagram. It should be noted that, only passing through the paths appear in the diagram, a contour can change its shape into a contour of another shape.

The process diagram was originally introduced to describe the static relation between contours. We utilize it in order to describe the dynamical change of a contour shape of X-ray heart images. The trajectory path in the process diagram describes the change of contour shape of a non-rigid body object. We applied it for description and analysis of dynamical change of the shape in medical images.

LEVEL1 -- Number of extrema is 4

LEVEL2-- Number of extrema is 6

Fig. 4 An example of classification

Fig. 5 Examples of processes

Fig. 6 An Examples of shape connections with the processes

Fig. 7 A process diagram

4 Motion analysis of heart images

Our purpose is to describe the dynamic behavior of the contour change of the heart images qualitatively. The object is X-ray (DSA) images of a heart left ventricle, an example of which was shown in Fig. 2. The image was taken from a lateral direction. A series of images of one of expansion-contraction cycle of heart taken at every 1/30 seconds was used.

It is common to divide the contour of heart left ventricle image taken from front right lateral direction into seven segment regions corresponding to the ruled domains of the every coronary arteries. The contour segments of those regions are shown in Fig. 8.

Figures 9 and 10 are the images of the expansion and contraction phases of a normal left ventricle and those of a disease heart, respectively. In the case of the normal heart, wall movement is fully made through out the expan-

Fig. 8 Region segments of left ventricle wall contour

Fig. 9 Expansion and contraction phases of a normal heart

Fig. 10 Expansion and contraction phases of a disease heart

sion-contraction phases as shown in Fig. 9. On the other hand, with the disease heart, since a part of heart muscle stops moving or a part is enlarged, compared with the normal heart, distortion of the movement arises in the contour shapes. In Fig. 10, a drop of local wall movement between near the top portion (segment 3) and the front side wall (segment 2) is seen. As shown in these figures, in a disease heart, it is known that the parts of the drop of movements mainly appear at the segments 2 and 4 of Fig. 8. Then, especially we concentrated to observe and express the contour shape movements of the segments 2 and 4.

5 The diagram for real heart images

5.1 Extraction of the features

In this research, the motions of the segments 2 and 4 of Fig. 8 are observed. We denote those segment portions with T1 and T2, respectively, which are shown in Fig. 11, and their curvatures with κ_1 and κ_2 .

Figure 12 shows the definition of T1 and T2 portions. The boundary between the extracted left atrium and the left ventricle domain is specified beforehand. Then, we place the axis from this boundary to the top of the heart, and extract T1 and T2 portions as shown in the figure. Although the contour produced with the snake had smooth contour curve to some extent, we fit the contour portions T1 and T2 with quadratic curves, and obtain the curvatures κ_1 and κ_2 from the coefficients of the curves.

5.2 Composition of a diagram

A set of curvature pairs κ_1 and κ_2 for a series of images are calculated as mentioned above. Then, the differences $\Delta\kappa_1$ and $\Delta\kappa_2$ of κ_1 and κ_2 of the sequential frames are derived. From the amounts of $\Delta\kappa_1$ and $\Delta\kappa_2$, the processes worked on those portions are identified and labeled. The label corresponding to the process is interpreted as follows (Fig. 13).

Fig. 11 Portions T1 and T2, and curvatures κ_1 and κ_2 on the contour

Fig. 12 Definition of T1 and T2 portions

Fig. 13 Relation between a label and a process

Fig. 14 2-dimensional diagram whose vertical axis is κ_1 and horizontal axis κ_2

Table 1. Curvature changes and process labels

Signs of curvatures	Label	Change of shape
$\Delta\kappa_1 > 0 \ \Delta\kappa_2 > 0$	PP	Top and bottom become convex
$\Delta\kappa_1 > 0 \ \Delta\kappa_2 = 0$	PK	Top becomes convex
$\Delta\kappa_1 > 0 \ \Delta\kappa_2 < 0$	PS	Top convex and bottom become concave
$\Delta\kappa_1 = 0 \ \Delta\kappa_2 > 0$	KP	Bottom becomes convex
$\Delta\kappa_1 = 0 \ \Delta\kappa_2 = 0$	KK	No change
$\Delta\kappa_1 = 0 \ \Delta\kappa_2 < 0$	KS	Bottom becomes concave
$\Delta\kappa_1 < 0 \ \Delta\kappa_2 > 0$	SP	Top concave and bottom become convex
$\Delta\kappa_1 < 0 \ \Delta\kappa_2 = 0$	SK	Top becomes concave
$\Delta\kappa_1 < 0 \ \Delta\kappa_2 < 0$	SS	Top and bottom become concave

- $P(\Delta\kappa > 0)$: The process of pushing
- $K(\Delta\kappa = 0)$: Keeping the shape
- $S(\Delta\kappa < 0)$: The process of sinking

Fig. 15 The meanings of the patterns in the diagram

Fig. 16 A 3-dimensional diagram

The combinations of two curvatures $\Delta\kappa_1$ and $\Delta\kappa_2$ and their labels are listed in the Table 5.2. In order to express this combination as a process diagram, a graph is introduced which took κ_1 as the horizontal axis and κ_2 for the vertical axis as shown in Fig. 14. In the figure, corresponding shapes to the graph are shown.

Pairs of (κ_1, κ_2) in the expansion-contraction cycle are plotted in the diagram of Fig. 14. The total process will appear as a pattern. In Fig. 15, examples of those patterns and their meanings are shown.

The motions of normal and disease hearts are described as the locus patterns in the diagrams. The pattern expresses a relative change of the curvatures at T1 and T2 portions. Even though there exists individual difference in heart shapes, this pattern shows how the segments of T1 and T2 portions moved currently. Therefore, there possibly obtains the same description of patterns, if the motion is same even with different original shapes. That is, it can express the heart motion in understandable visual form helpful for the diagnosis.

5.3 3-dimensional diagram

Figure 16 expresses the occurrence and change of a process in 3 dimensions. In this diagram, the vertical axis is taken as a size of the left ventricle. When there is no difference in the size of a left ventricle, that is, expansion-contraction movement does not fully appear in the respective phases, the locus of the vertical direction becomes short. This indicates the difference of the rate of expansion for the same 2-dimensional diagram pattern.

Fig. 17 Contours of a normal heart 1 in contraction and expansion phases

Fig. 18 Contours of a disease heart 1

Fig. 19 The diagram of normal heart 1 (Fig. 17)

Fig. 20 The diagram of disease heart 1 (Fig. 18)

6 Experimental results

6.1 2-dimensional diagram for real images

In this chapter, the results of diagram expressions are shown including normal and disease hearts.

Figure 17 is the contour of the normal heart which is fully expanding and contracting both in the T1 and the T2 sides. On the other hand, Fig. 18 is of the heart of the myocardial-infraction patient, and the T1 side (front side wall) is hardly moving.

The diagram figure of Fig. 19 for the Fig. 17 shows that the locus lies in the direction where T1 and T2 portions correspond to fully moving, that is, $\Delta\kappa_1$ and $\Delta\kappa_2$ increase and decrease synchronously. On the other hand, the diagram in Fig. 20 for the contours in Fig. 18, since the movement of T1 is small, indicates the amount of change of $\Delta\kappa_1$ is small and the locus is limited within a narrow region.

Figure 21 shows a diagram of another normal heart, and Fig. 22 is that for the heart whose T1 portion does not move. Since a locus pattern describes relative changes of T₁ and T₂ portions regardless of their initial shapes, from the diagrams in Figs. 20 and 22, it is interpreted that their motions are hardly seen for these hearts, especially in the T1 portion.

Fig. 21 The diagram (Normal heart 2)

Fig. 22 The diagram of the disease heart 2 in expansion phase

Fig. 23 The 3-dimensional diagram (normal heart and expansion phase) of Fig. 19

6.2 3-dimensional diagram

Figure 23 is the 3-dimensional diagram pattern of the normal heart of Fig. 19. Figures 24 and 25 are the 3-dimensional diagram patterns of disease hearts of Figs. 20 and 22, respectively. Because the contraction does hardly seen in Fig. 25, the locus of the vertical direction seems to be short.

7 Conclusions

This research proposed a method for describing the motion pattern of the heart contour by introducing the process diagram, and showed it could distinguish the difference between normal and abnormal heart motions in

Fig. 24 The 3-dimensional diagram (heart 1 and expansion phase with a disease) of Fig. 20

Fig. 25 The 3-dimensional diagram (heart 2 and expansion phase with a disease) of Fig. 22

their X-ray images. By this method, overcoming the individual differences, the qualitative expressions for the portions which moves or does not move are enabled. This provides methods promising an automatic diagnosis for the X-ray heart images.

We are considering the extension of the method to describe the 3-dimensional surface motions.

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