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Improving the precision of omni-directional M-mode echocardiography systems

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ABSTRACT

The first generation of omni-directional M-mode echocardiography system is able to extract implied motion information from sequential echocardiography images. However, in recent years, there has been an increasing demand in clinical practice for more precise dynamic motion information and research into the second-generation of omni-directional M-mode echocardiography systems has focused on how to achieve this greater precision. Two possible approaches are to improve the acquisition precision of echocardiography and to improve the extraction accuracy of motion curves. Firstly, we describe the use of a model for separation of cardiac 'non-functional' movement, in the design of a particle swarm optimization (PSO) algorithm to track and analyze the heart feature points, in order to achieve improved omni-directional M-mode echocardiography using tracking sampling lines. We then present the design of a new method for heart motion curve extraction, based on the idea of multi-scale analysis and wavelet transformation, which can suppress image noise effectively and thereby reduce the need for manual intervention. Experimental evaluation indicated that these techniques produce more effective results than the first generation omni-directional M-mode echocardiography system.

1. Introduction

A major difference between the heart and other organs is its movement and deformation, which means that ultrasound images of the heart contain rich and valuable cardiac motion information. The issue of how such information may be accurately extracted is of international interest. The first generation of omni-directional M-mode echocardiography system [1] can construct omni-directional grey (position)-time waveform diagrams in any directional sample line. Therefore, they can be utilized in the measurement of any structure and any direction of heart tissue in ultrasound images [2]. The boundary of the heart tissue appears as grey in omni-directional M-mode echocardiography; therefore the grey (position)-time waveform represents the movement-time waveform of the heart tissue. Our patent "omni-directional M-mode echocardiography method and system" (Chinese national invention patent ZL98125713.5) describes the movement-time waveform of heart tissue. Another patent, "a method and device for detecting omni-directional M-mode echocardiography velocity and acceleration" describes a method to obtain motion information by detecting velocity and acceleration, which is calculated from the movement curve by the first-order differential and the second-order differential respectively (Chinese national invention patent ZL2003101042840). However, the precision of the results yielded by these operations is strictly dependent on the accuracy of the derived movement curve [3].

In order to extract more precise motion information, we considered the following two issues:

a) In the first-generation omni-directional M-mode echocardiography system, the sampling line is fixed and the waveform is constructed from the movement of the grey (heart tissue boundary) along the sampling line, plotted against time. However, the heart wall motion comprises the interaction between the structure's functional movement [4], which includes systolic and diastolic deformation, and non-functional composite movement, which includes translational and rotational movement caused by breathing and blood flow. This non-linear [5] motion of the heart wall leads to a problem in the existing omni-directional M-mode echocardiography system. The original heart tissue position on the fixed sampling line does not always move along this line; sometimes it moves in other directions. Thus the reconstruction of the grey (position)-time waveform in these moments will no longer represent the original location of the structure and therefore

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cannot accurately reflect the heart's movement. Other international echocardiography motion detection methods, such as M-type [6] and tissue Doppler [7], also suffer from this problem. The existence of the problem is generally known, but there has been little research aimed at solving it. Most work has been focused on avoiding the problem by finding a point where the composite movement is minimized, so that the measured point on the heart tissue moves out of the sampling line as little as possible in the detection phase.

b) In the first generation of omni-directional M-mode echocardiography system, the motion curve detection algorithm was designed according to the movement characteristics of the heart. It detects the target motion curve based on interpolation information for the curve under consideration, progressively using linear search templates in the effective search range. However, this method cannot automatically remove false edges and noise, and requires more human (doctor) intervention. Essentially, the border points between the blood and the chamber wall tissue move along the sampling line plotted along the time axis, which forms the movement curve. However, as this is indirectly derived from the two-dimensional ultrasound image sequences, the omni-directional M-mode image quality is inevitably influenced by the quality of those ultrasound images. An ultrasound image is characterised by fuzzy and uneven features and this is a serious impediment to the accuracy of the edge extraction process. Thus, there is an urgent need for a more suitable movement curve extraction algorithm in the second-generation omni-directional M-mode echocardiography system.

We therefore focused on incorporating two major elements into the design of the second-generation omni-directional M-mode echocardiography system; improvement of waveform acquisition and improvement of the method of motion curve detection.

2. Improvement of waveform construction

2.1. Waveform acquisition

In the first generation omni-directional M-mode echocardiography system, the sampling line is fixed; therefore the grey (position)-time waveform diagram represents the total movement of the tissue, which comprises both functional and non-functional movement. This system is prone to the detected position disengaging from the sampling line due to the non-functional movement, which introduces movement 'noise'.

The guiding principle of the second-generation system is to track the motion of some particular tissue of the heart, thereby obtaining a priori knowledge of the nature of the motion in order to establish the equivalent movement sampling line. This is used to guide the separation of movement 'noise'; i.e. non-functional movement, from the functional movement of the measured area of the heart.

We present a precise tracking design for the omni-directional M-mode echocardiography system—a four-dimensional tracking model for heart deformation and a particle swarm optimization (PSO) for analyzing the model – in order to establish the equivalent movement sampling line (also known as the tracking sampling line) to guide the tracking for omni-directional M-mode echocardiography reconstruction.

Tracking according to a 'point' cannot be achieved, because ultrasound images contain a great deal of noise and speckles, which means that a point cannot completely reflect the area characteristics and is subject to a greater impact from noise. Therefore, the system draws upon the idea of block matching, using as a tracking object the small region of an image sub-block in which the feature point lies. The image sub-block is more able to accurately reflect the changes in the relevant part of the heart during the movement [8,9].

2.2. System model

The system assumes that the heart is a deformable body that has systolic and diastolic cardiac motion and also translational and rotary motion. The selected feature point is set to $P_p(x_p, y_p)$, which is used to represent the centre of a small area. This small area is represented by $P(w_{pi}, h_{pi})$, where (w_{pi}, h_{pi}) are the coordinates of points within the feature area pattern relative to $P(x_p, y_p)$, the centre of the area pattern, and $P(*)$ represents the grey of the image. Then the sequence of points representing an area pattern to be matched can be described as:

$$P = \{(w_{p0}, h_{p0}), (w_{p1}, h_{p1}), ..., (w_{pN-1}, h_{pN-1})\} \tag{1}$$

If we scale the area by a factor of M (representing the cardiac diastolic and systolic motion within the search area), rotate about the origin point θ degrees (representing the cardiac rotary motion within the search area) and translate to (w_k, h_k) (representing the cardiac translational motion within the search area), then these conversions map point sequence P to point sequence Q:

$$Q = \{(w_{q0}, h_{q0}), (w_{q1}, h_{q1}), \ldots, (w_{qN-1}, h_{qN-1})\} \tag{2}$$

The point sequence mapping between Q and P is as follows:

$$\begin{bmatrix} w_{qi} \\ h_{qi} \end{bmatrix} = M * \begin{bmatrix} \cos\,\theta - & \sin\,\theta \\ \sin\,\theta - & \cos\,\theta \end{bmatrix} * \begin{bmatrix} w_{pi} \\ h_{pi} \end{bmatrix} + \begin{bmatrix} w_k \\ h_k \end{bmatrix} (i = 0, 1, ..., N-1) \tag{3}$$

We define the feature point and the surrounding sub-block identified in the first frame as the pattern that we then attempt to recognize in each of the subsequent frames. An evaluation standard parameter value should be defined to measure the degree of matching. Thus, we firstly define the image sub-block around the feature point in the front frame, and then calculate the optimal four-dimensional parameters (v, w, θ, M) within the range of the rear frame.

The best alignment will be achieved when the maximum fitness estimated parameter value is based on the optimal four-dimensional parameter conversion.

In order to improve the tracking speed of image sequences, the system uses the PSO algorithm to achieve tracking between successive feature points [10]. Using the PSO algorithm helps to reduce the search space and improve the efficiency of tracking. The tracking design of our omni-directional M-mode echocardiography system is based on the PSO algorithm [11] from three aspects, namely encoding, inertia weight and estimation function.

2.3. Algorithm flow

As stated above, the first step is to determine a strongly characterized feature point in the first frame. Then this feature point is tracked through each subsequent frame until the final frame is reached. On each iteration, the system uses the PSO algorithm to calculate the optimal four-dimensional parameter between the two frames, then adjusts the control parameter and computes the image transformation according to the four-dimensional parameter. It then uses the value of the transformation-invariant characteristics of the feature region to evaluate the fitness value between the two image frames. Finally, based on the fitness value, it updates particle speed and position; this iteration continues until the last generation, at which point it outputs the optimal particle four-dimensional parameter as the best matching position.