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Spatial and spatio-temporal feature extraction from 4D echocardiography images

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ABSTRACT

Background: Ultrasound images are difficult to segment because of their noisy and low contrast nature which makes it challenging to extract the important features. Typical intensity-gradient based approaches are not suitable for these low contrast images while it has been shown that the local phase based technique provides better results than intensity based methods for ultrasound images. The spatial feature extraction methods ignore the continuity in the heart cycle and may also capture spurious features. It is believed that the spurious features (noise) that are not consistent along the frames can be excluded by considering the temporal information.
Methods: In this paper, we present a local phase based 4D (3D+time) feature asymmetry (FA) measure using the monogenic signal. We have investigated the spatio-temporal feature extraction to explore the effect of adding time information in the feature extraction process.
Results: To evaluate the impact of time dimension, the results of 4D based feature extraction are compared with the results of 3D based feature extraction which shows the favorable 4D feature extraction results when temporal resolution is good. The paper compares the band-pass filters (difference of Gaussian, Cauchy and Gaussian derivative) in terms of their feature extraction performance. Moreover, the feature extraction is further evaluated quantitatively by left ventricle segmentation using the extracted features.
Conclusions: The results demonstrate that the spatio-temporal feature extraction is promising in frames with good temporal resolution.

1. Introduction

Cardiovascular disease (CVD) is the leading cause of deaths worldwide and kills more people than any other disease [1]. The cardiac imaging is frequently employed to assess the CVD. In this respect, the echocardiography is the primary cardiac imaging modality due to its low-cost, harmless nature and quick acquisition. The left ventricle (LV) is the most important heart chamber for diagnosing CVD since it is responsible for supplying nutrient-rich blood to the entire body. For performing the analysis, the LV needs to be segmented to carry out the cardiac functional analysis. One of the common approaches for LV segmentation is the deformable contour based approaches in which a contour is inflated or deflated towards the boundaries [2] driven by the image edge information. However, quite often, the LV segmentation may not be totally successful due to the variations in contrast around the LV. Hence, for a successful delineation, the reliable boundary features need to be extracted as a preprocessing step. The features of interest here correspond to the LV endocardial and epicardial boundaries. These boundaries are considered to exhibit step edge characteristics in previous work [3–6].

The echocardiography images typically suffer from poor image characteristics which include: intensity dropout, low contrast, low signal to noise ratio and speckle appearance. These characteristics make feature extraction a challenging task. Current intensity based feature detectors typically do not work well with the ultrasound images [7]. An approach known as local phase based measure has been proposed in the literature [8] which is theoretically independent of low contrast and noisy nature of the ultrasound images.

Our research is inspired by Mulet-Parada's work [3] which extended the spatial feature extraction to spatio-temporal feature extraction. Their proposed idea was to avoid the speckle and other spurious artefacts that are not consistent along the consecutive frames by developing a 2D+T version of the feature asymmetry

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measure. In this paper, therefore, we study the spatial 3D and spatio-temporal 3D+T feature extraction to explore the impact of time information. We adopt a local phase based feature asymmetry (FA) measure using the monogenic signal proposed in our earlier work [7].

This paper is organized as follows: Section 2 reviews the related work on local phase based feature extraction. Section 3 provides a background of the local phase based feature extraction method. Section 4 presents the phase based method for spatio-temporal 4D feature extraction from the 3D+T echocardiography images. The process of surface based LV segmentation is also described in this section. Section 5 describes the experimental setup and presents the results of feature extraction using spatial (3D) and spatio-temporal (4D) extension of the FA measure. The qualitative and quantitative results are also discussed in this section. Section 6 finishes the paper with summary and concluding remarks.

2. Related work

The local phase based methods have attracted a lot of attention recently in medical image analysis [9–13] and notably in ultrasound images where these methods are relevant due to the low-contrast nature of these images. Here, we present a review of some relevant work with local phase based methods in ultrasound images.

In our earlier work, we proposed [14] multi-scale FA measure derived from local phase approach for the detection of endocardial, epicardial and myocardial centreline for 2D echocardiography images. In this work, the monogenic signal [15] was used that makes use of isotropic Riesz filter (no orientation selection is required). In our later work, we proposed [7] the multi-scale FA measure for the extraction of endocardial and epicardial boundaries from 3D echocardiography images using the monogenic signal. The use of monogenic signal greatly reduced the time complexity contrary to the use of oriented filters [3,16]. Moreover, the feature extraction was improved using the multi-scale feature asymmetry measure.

Patwardhan [17] proposed a method for automatic detection of salient region (gall bladder, blood vessels, etc) from ultrasound images. Their approach uses local phase information for identifying the regions with spatial symmetry. In order to extract these regions, they employed the feature symmetry measure.

Hafiane et al. [18] presented a method for the automatic detection of nerve blocks from ultrasound images to assist the anaesthetist for injecting anaesthesia in nerve block of a particular body region. They adopted gradient vector flow contour for segmenting a nerve block and provided the FA measure based edge as an input. The FA measure was computed using the monogenic signal employing the Cauchy filter.

Antunes et al. [19] proposed an automated segmentation method for extracting all the four cavities simultaneously from echocardiography images of children. As a pre-processing step, the local phase was computed for extracting the boundary features of all the cavities using phase based feature symmetric (FS) approach. Antunes et al. [20] compared their segmentation methodology for extracting all four cavities with watershed segmentation and three other alternative level set methods and found their segmentation to be better than other methods.

Belaid et al. [6] proposed the phase based level set segmentation of 2D echocardiography images. The main focus of this study was on quantitative comparison between various semi-automatic segmentation algorithms. Before segmentation, the feature extraction was performed as a pre-processing step using the FA measure. They also used the multi-scale FA measure using the monogenic signal and employed the Cauchy filter for feature extraction of the LV boundaries. The extracted features were then given as an input to various semi-automatic segmentation algorithms.

Hacihaliloglu et al. [21] used the local phase information to enhance the bone surface localization and visualization in 3D bone images. They have presented the potential of this phase based information by comparing the results with intensity gradient based method. Their results have shown good performance where the phase congruency detected bone surface with no visible error while the gradient approach (Canny) showed some localization error and is very much affected by the speckle noise. Moreover, they have also experimented on the ability of phase based method to find small gaps between fragments and found it accurate and reliable in comparison with the gradient based method.

Rahmatullah et al. [22] integrated the local features from an intensity image and global features extracted by the FA measure. In their proposed algorithm, they used phase based global features along with local Haar features for detecting the stomach and umbilical vein from 2D fetal ultrasound abdominal images. Their approach has significantly improved both the detection rate and the speed.

Sanchez-Ortiz et al. [23] presented the automatic acquisition of 3D echocardiography images and automatic analysis of the LV function. In their proposed methodology, the LV endocardial boundary features were extracted using a 2D+T local phase based method. The use of phase based representation of echocardiography for registration purpose can be found in the literature [24,25].

Mulet-Parada et al. [3] used the phase information for feature extraction from the echocardiography images for the first time. They experimented with 2D and 2D+T images using the FA measure and employed an oriented log-Gabor filter [26]. Their 2D FA measure showed good results but with small flickering spurious features when displayed as a movie sequence. The results of 2D+T boundary detection showed a considerable reduction in the false flicker features. However, the 2D+T detection had a limitation of not tracing the fast cardiac motion such as movement of the valves similar in temporal characteristics to speckle. The reason for this problem was the low frame rate of the used image sequences and not necessarily a limitation of the proposed algorithm. The authors claimed that this problem can be overcome by increasing the temporal sampling rate (i.e. frame rate).

To the best of our knowledge, there has been no previous work on spatio-temporal 3D+T feature extraction from 4D echocardiography images. In this paper, we explore the spatio-temporal 3D+T feature extraction and compare it against the 3D feature extraction both qualitatively and quantitatively.

3. Local phase and feature asymmetry

In this section, we provide a brief background about the local phase and the feature asymmetry measure. The phase of an image contains information about the feature location and orientation while amplitude provides the intensity information [6]. Oppenheim et al. [27] have shown that when the phase of an image is combined with the amplitude of another image, it will result in a new image carrying features of the image whose phase information was considered. For the local phase computation, a complex representation of the signal called analytic signal is required. For a 1D signal $f(x)$, the complex analytic signal is composed by taking the original signal and its Hilbert transform, as follows:

$$f_A(x) = f(x) + i f_H(x) \quad (1)$$

where $i = \sqrt{-1}$, $\boldsymbol{f}(\boldsymbol{x})$ represents the original signal while $\boldsymbol{f}_{\boldsymbol{H}}(\boldsymbol{x})$ represents the Hilbert transform of $\boldsymbol{f}(\boldsymbol{x})$ computed by the convolution of $\boldsymbol{f}(\boldsymbol{x})$ with Hilbert kernel $(1/\pi x)$. The $\boldsymbol{f}_{\boldsymbol{A}}(\boldsymbol{x})$ forms a