Cardiac Optical Mapping Using Frequency Filtering Techniques for Low Resolution Cardiac Images

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INTRODUCTION

Cardiac optical mapping is a technique used to study the electrical activity of a heart. This mapping is done using a voltage-sensitive dye that reacts to a specific light source causing a fluoresce reflection according to muscle cell activity [1]. An optical filter is used in order to register signals within a   wavelength range around 600 nm. A CCD camera, with a 60x60 pixel spatial resolution [2].

The present work receives different video files corresponding to different experiments, thus different rat hearts images. Two different types are used the DALSA and the ΔF format.

The vision system output video file introduces a DC voltage in order to distinguish a signal with intensity level zero from a system disconnection. The signal has a 12-bit resolution, over a 0-5 volt span.

The first stage consist on removing this DC level and perform a signal rescale to 8-bit resolution. The signal is then process to reduce the noise level, enhance borders, create an automatic mask for the heart and finally calculate action potential duration.

Loading Scaling De-trend	1D Filtering FFT	2D Filtering Spatial Fourier Automatic Mask	Action Potential Duration

Figure 1: Sequence of tasks

Figure 1 shows the different steps followed to find the Action Potential Duration (ADP), the functions for loading video, filtering, video speed control, automatic mask generation and time interval are implemented as GUI interfaces in Matlab.

For most of the work there is no golden reference to compare with, so it is performed between implemented algorithms. Three pixel regions are define to work : a) border region, b) center region, c) an intermediate region with pixel coordinates (58,30), (30,30) (45,45) respectively. For Action Potential Duration section a 9x9 pixels reference image frame with known signals is used as reference.

The Mean Squared Error (MSE) is used to quantify the differences between methods. Values below 1 (MSE<1) are considered acceptable. For filtering comparison RMSE is also used.

METHODS

Video interface

The GUI allows to load a file, dalsa or ΔF format, control frame rate visualization and the selected sequence frames. It also allows to see the time-pixel signal with a mouse over functionality. The differences between a polynomial fitting, *polyfit,* and the conventional Matlab *detrend* function can be also observe in the time signal window. A snapshot of the GUI is shown in figure 2.
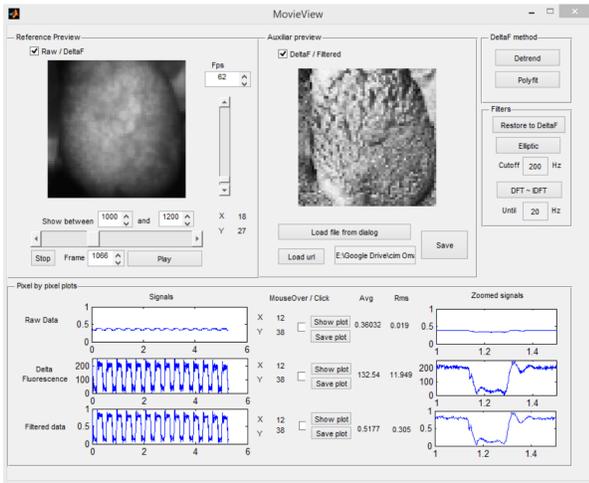
Figure 2: Graphical interface: load, visualize, remove trend and filtering

Filtering

As a first approach to filtering, a spectral content of the signals is calculated in order to determine the expected bandwidth.
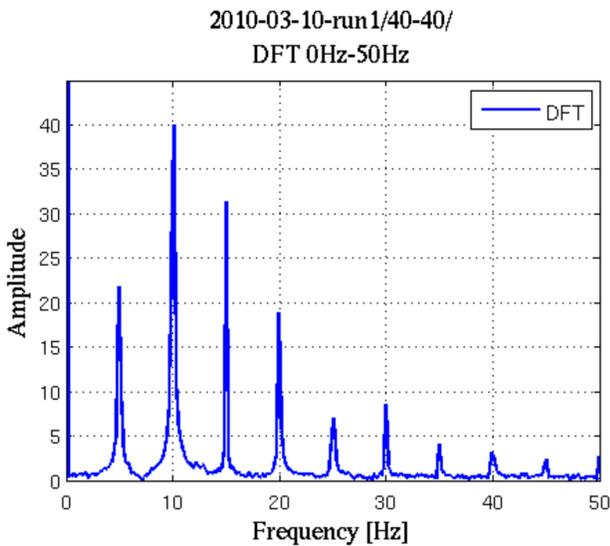
Figure 3: Center region pixel Frequency content

Figure 3, shows the frequency amplitude contents of a intermediate region pixel (40,40) it shows that the main components are between 0Hz and 20 Hz, thus a cutoff in 50 Hz for filtering is selected [3].

Different filters are tested, Butterworth, Equiripple, Chebyshev (Type I and II) and Elliptic.

Region Growing

Using an image editor, a manual segmentation is made as reference for checking the accuracy of the automatic algorithm; both the original image and the manually segmented image can be seen in Figures 4.a. and 4.b.
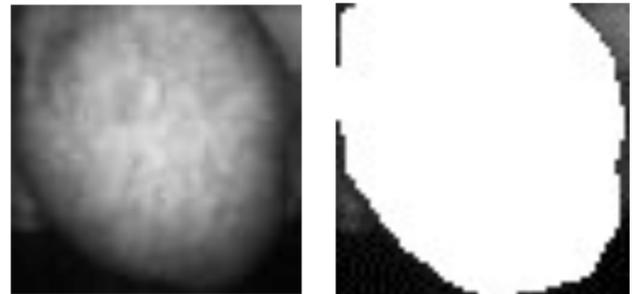
Figure 4.a. and 4.b.: Heart Image and Manually generated Mask

A region growing method based on histogram and different pixel seed selection is implemented. First step, is to find an intensity pixel value that is representative of all frames in the video. This done by a median filter over all the video frames is applied. This also allows to find the pixel position that serves as seed for the growing seed.
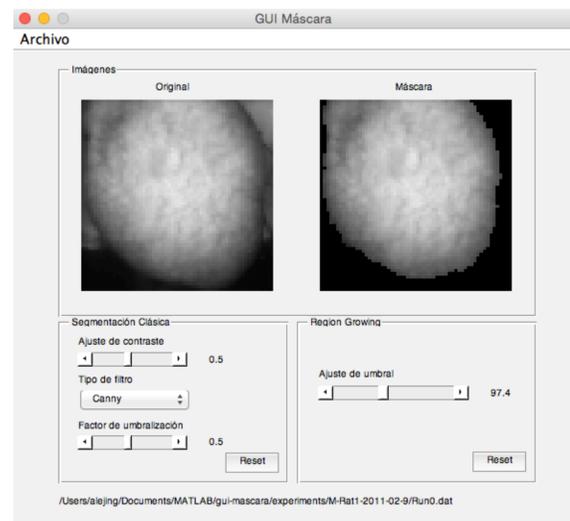
Figure 5: Region Growing GUI interface

In figure 5, an example of the GUI is shown, also it can be filtered using conventional border enhancement algorithms such as *canny*, *sobel*, and to select the thresholding level. The contrast level can be adjusted by a slider.

Action Potential Duration

In order to estimate the duration of a pulse three different methods are studied: a) Percentage of Maximum Point. b) Polynomial Fit. c) Fundamental Frequency Correlation. First one is implemented only in a period of the signal, it seeks to find the maximum in the derivative function of the signal and a percentage of the maximum of the signal as a deactivation time. Second one splits the signal into two components, the raising and the falling segment. It attempts to fit polynomials functions on each segment. The third one tries to find the fundamental frequency of the signal region and approximate the pixel duration signal through a correlation with the signal with the same fundamental frequency.

Percentage of Maximum Point

The first step to use this technique is align the action potentials of each pixel in the video. Alignment was done using the correlation between the first and the rest of the slices of the pixel signal, and then shift the correlation signal. It is necessary to use a trimmed mean to exclude outlier's spikes because signals are not perfectly time spaced.

With a pattern signal, i.e. the first pulse in the signal, the upstroke maximum derivative is calculated through the Matlab's *diff* function. It is used as the peak's activation point. The deactivation time is determined by finding the time at which maximum of the signal falls to a desired percentage. The action potential duration is the difference between the two points and this value is stored in a matrix in which each element represents a pixel of the analyzed video

Polynomial Fit

As the former, this method is limited to analyze one action potential, so the first step is the same as the above. The action potential signal maximum is found and then it is used to split the signal into rising and falling edge regions (up and down section of the curve). In the rising section, a polynomial is fitted to the curve to identify the baseline and maximum values, as well as to determine the 20% and 50% percent of the maximum values. A polynomial fit was chosen since the variation between different actions potentials shapes found in the pixel signal is deemed to be adequate by manual validation of the fit for several data sets [4].

The activation time corresponding to the 50% of the maximum value was found by taking the absolute values of the subtraction of the 50% value from the curve, like removing the offset of a signal, and finding the curve minimum in that region. This method is acceptable in this situation because the monotonic curve characteristic over the time-interval analyzed.

The same method is used on the falling edge interval to identify the time of the 20% of the action potential falling side maximum. The difference between the times of the rising and falling edges gives what we defined as the 80% action potential duration.

Correlation with Fundamental Frequency

Due to the different shapes of action potentials and its dependency of the region of the heart, a neighbourhood behaviour is intended to estimate. A mask of 5x5 pixels is taken, and time Fourier transform is calculated for each element in the mask in order to obtain the fundamental frequency of the region analyzed, obtained by a median value calculation.

A cross-correlation between a fundamental frequency sinusoid found previously and each pixel in the mask is calculated, normalized and finally the maximum value is obtained to generate the optical map of action potential durations.

RESULTS & ANALYSIS

Filtering

Table 1 presents result comparison between *detrend* and 3rd order *polyfit*.

Table 1: Detrend vs Polyfit 3rd grade

REGION	MAX	MIN	MSE
Border	0,27	$1,23x10^{-5}$	$6,2x10^{-3}$
Center	0,26	$1,61x10^{-5}$	$8,1x10^{-3}$
Intermediate	0,79	$8,76x10^{-5}$	$7,0x10^{-2}$
Border1	4,42	$4,39x10^{-4}$	2,2

The table shows that the MSE is generally much less than 1, with the exception of pixels on border1 zone, in which there is an error of 200% with respect to the acceptance, in this region is difficult to extract real heart signals form the background. This examples reinforces the need to make a mask to process only heart signals. According to the table a polynomial fit can be used as an alternative to *detrend* function, with good results.

The equiripple filter performance is worst of all, Butterworth and Chebyshev Type I have acceptable performance. Elliptic and Chebyshev Type II have the best performance as its shown in figure 4.
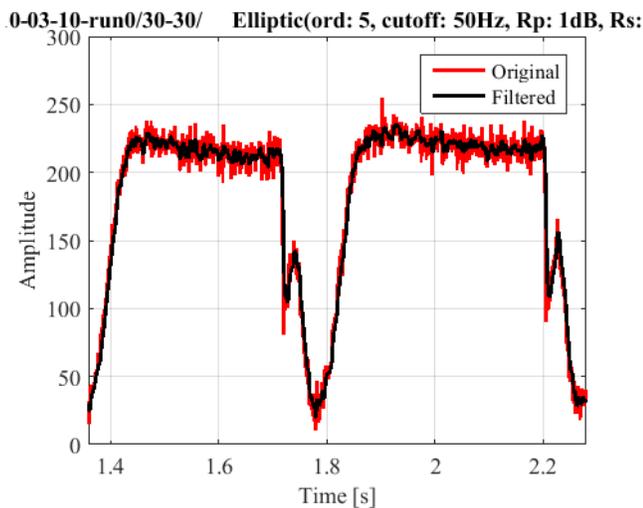
Figure 4: Elliptical filter center region

As an alternative, a signal reconstruction using the Discrete Fourier Transform (DFT) was performed with better results especially since there is no phase shift and less noise. Figure 5 show the reconstruction obtained with a 50 Hz limit.
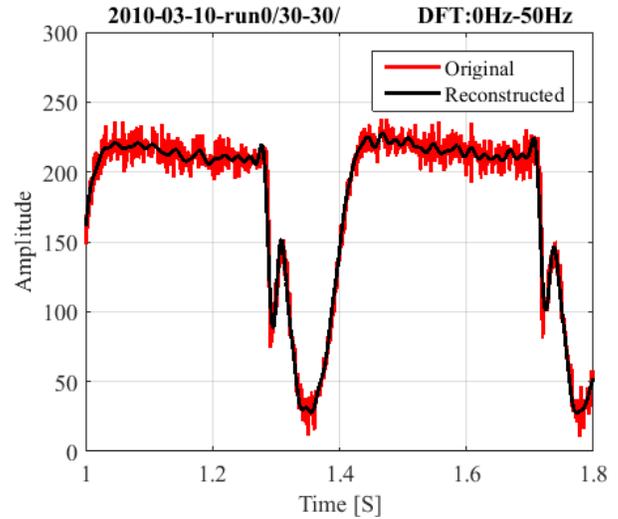
Figure 5: Signal reconstruction using DFT

Region Growing

A comparison between the results of the manual mask and the automatic generated mask is shown in figure 6.
The comparison is made base on the pixel area and pixel perimeter, the automatic is smaller by 10.3% in the area and by 3% in the perimeter. A correlation between images is also performed giving a 75% of similarity.

Reference image Figure 2	Practical image Figure 3
Perimeter: 206.7 pixels	Perimeter: 200.5 pixels
Area: 2964 pixels^2	Area: 2660 pixels^2
Perimeter difference (%): 3.0%	
Area difference (%): 10.3%	
Correlation coefficient between the images: 0.75	

Figure 6: Comparison Manual vs. Automatic Mask

The best results regarding the approximation to heart's area and perimeter is found when the seed is located in the center of the image (30,30), the values are below 3% in percent and below 11% in area.

Table 2: Automatic mask generation results

Experiment		Results %		
#	Seed	Per.	Area	Corr.
1	(15,15)	2,2	9,6	74
1	(30,30)	1,2	9,6	72
1	(58,30)	27,4	3,8	52
2	(15,15)	4,2	11,1	74
2	(30,30)	2,8	10,1	71
2	(58,30)	12,4	7,1	56
3	(15,15)	1,8	9,7	70
3	(30,30)	1,8	9,4	71
3	(58,30)	5,2	13,9	59

Action Potential Duration

In order to test the algorithms to estimate the ADP, simulated signal are implemented as shown in figure 8. It shows the fourier reconstruction and polynomial fitting.
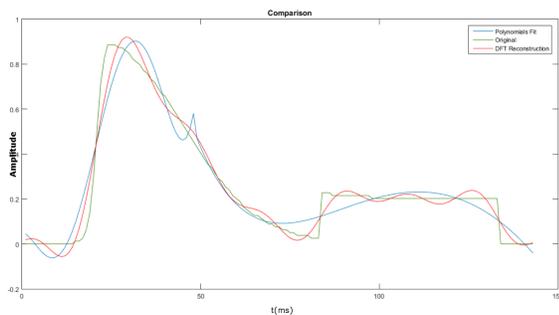
Figure 7: One period pixel signal approximation

The polynomial fitting shows poor tracking of sudden signal changes, besides it has unwanted peaks in the falling region. As a reference two different observer determined the activation interval.The signal reconstruction made by Fourier reconstruction gives better adjustment to the interval with an 12,7% error average compare to the 27,3 % of the polynomial for all the video. On the central region it rises to 24% and to 45% respectively.

Based on the percentage method colormap image using the automatic mask for the APD is created as shown in figure 8.
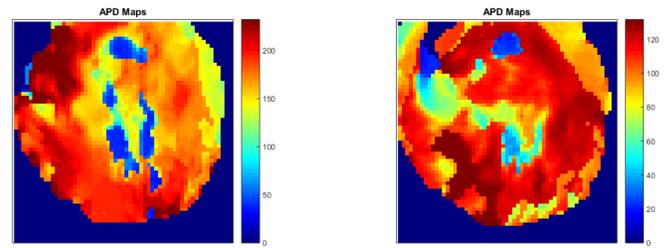
Figure 7: One period pixel signal approximation

CONCLUSIONS

The use of the Fourier transform is useful for filtering the intensity pixel signal since introduces no phase shifting and reduces notably the noise content.

It has potential also as an estimation of the action duration interval but further work is requiere to extend it to the whole signal span.

The approximation of the duration interval using the percentage algorithm gives a promising tool for creating the activation maps.

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