Image Processing Methods for Diagnostic and Simulation Applications in Cardiology

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***Abstract*—The paper describes two particular applications of image processing for the purpose of analysis and simulation in the field of cardiology. The authors describe a method which allows for combining the 2D image obtained in ECHO examination, and a 3D model of heart, extracted from a set of CT slices. The fused image provides an intuitive view on the contractual function of heart, by overlaying the bull's eye diagram on the model of left ventricle. By preserving the spatial information, it is possible to accurately point the location of areas with impaired contractual function. Another method described by the authors, displays the use of the CT volume for simulation of echocardiography images for purpose of training application. A simple approach based on pixel brightness adaptation is used to provide images of sufficient training quality. At the same time authors highlight the issues of storage and run-time memory requirement of such application, and suggest a method of reducing the working set size.**

***Index Terms*—cardiology, echocardiography, ECHO, image processing, simulation, USG**

I. Introduction

THE diagnosis and management of coronary artery disease (CAD) relies heavily upon medical imaging techniques implemented in nowadays examinations. A wide spectrum of imaging methods, that exploit different physical phenomena, require both skill and understanding for carrying out the examination and result analysis. These difficulties have been extensively addressed by introduction of computer based methods for data analysis and simulations.

II. Non-invasive Diagnostic

The first medical imaging technique was introduced at the beginning of XX century. In 1910, for the first time it was possible to look into human body in a non-invasive way, by exploiting X-ray imaging. From this date, the correlation between technical progress and diagnostic methods in medicine became much more significant. A lot of technical inventions found their way to be incorporated into medical diagnostic techniques, resulting in better, more scrutinised assessment of human health. To provide better view of organs, chemical agents were injected into body providing better contrast in medical X-ray images. These techniques are still in use in angiography. However, current work on new diagnostic methods is focused on non-invasive as preferred ones. The main reason is both, reduction in cost and execution time, however, at the expense of more complicated post processing.

Computed Tomography (CT) and ultrasonography (USG) are commonly applied in a variety of cardiology tests, where observation and analysis of human heart and neighbouring blood vessels function is of critical importance for final diagnosis. One of the most significant improvements in non-invasive medicine diagnostic techniques was the introduction of ultrasonography. Using this method it is possible to observe human organs and assess their function. ECHO (echocardiography [10]) techniques are an implementation of ultrasonography that allows to obtain a view of the heart. The ECHO projection makes possible to obtain images sequence of heart movement in real time. This technique is now in use in every cardiologic clinic for carrying out a quick assessment of patient's condition, thus replacing the invasive methods, at least at the initial stage of the diagnostic process. There is a variety of different examination methods which use ultrasonography, especially where the human heart and coronary arteries are an object of interest. In cardiology there are two sophisticated method to obtain view of heart and surrounding arteries-transthoratic and transesophageal echocardiography (TTE and TEE respectively). TTE is much easier to perform and is used for fast check-up. TEE provides a more detailed view of the heart and can be used as a definitive method, however all this can be obtained at the cost patient's comfort. The transesophageal echocardiography is covered in more detail in section IV.

Nowadays the most sophisticated and technically demanding procedures in medical practice is a computed tomography [8]. CT is an explication of x-ray method providing a different form of imaging known as cross-sectional imaging. CT technique is able to prepare sequential images of human organs. It is also possible to capture work movements of specific interior structures. By post processing algorithms execution medical staff is able to view 3D object of interest. Presented scene is prepared by applying images filtering algorithms and slices coordinates correlation. Next, evaluation stage of medical

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imaging is to prepare technical solution of merging the 3D object with other, separately performed examination. 3D projection is possible to be presented as hybrid image including needed data for diagnostic purpose. Examples of this technique will be show in details in following sections of this article.

III. CT and ECHO Images Fusion

Computed tomography coronary angiography (CTCA) and myocardial perfusion imaging techniques (single photon emission computed tomography, SPECT, or positron emission tomography, PET) are known as non-invasive modalities for the diagnosis of coronary artery disease (CAD) [16]. What is more, having in mind a patient complication minimalization after the examination, the paper authors decided to formulate a new, non-invasive method of cardiology inspection. Prepared technique of hybrid image is a combination of data from CT and ECHO. This visualization allows obtaining complementary morphological (heart, left ventricle and coronary anatomy) and functional (left ventricle) information in a single scene. From this perspective there is an opportunity to confirm possibility of the left ventricle (LV) abnormal function caused by stenosis. Next step in cardiology therapy will be medical decision of a treatment method-pharmacological or invasive intervention (bypass or percutaneous transluminalcoronary angioplasty -PTCA).

A. Implementation

Presented solution is based on images processing obtained from Computed Tomography. It is needed to possess 3D view of left ventricle with coronary including anatomical position information. From this data it is possible to extract 3D model of LV, coronary artery tree and surface of pericardium. On the other hand, from ECHO AFI (Automated Function Imaging) [11] output, the paper authors retrieve as bull's-eye representation [10] of LV function. These two images are processed and combination of them is presented as interactive 3D view, easy to manipulate and handy to medical stuff examination interpretation.

B. Algorithm overview

Modern CT scanners produce a volume of data that can be manipulated, and reformatted into volumetric, three-dimensional representations of internal human body structures. This data is exported and saved as a DICOM archive [15], common, medical data format in form of a sequence of cross-section slices of the structure. This data representation is able to be imported and used in further steps transformations. Raw data from DICOM files is treated as an input for segmentation algorithms to perform extraction of the object of interest. Using threshold processes it is possible to extract the object of interest as a collection of voxels representing its structure. Our goal is to prepare Triangulated Surface Mesh [12] of left ventricle and coronary. Extraction of surfaces from volumetric data can be achieved using modified Marching Cubes Algorithm. In this approach each 8 neighbour voxels are taken into consideration at a given time. Each set of 8 voxels forms edges of an imaginary cube. Applying a custom thresholding procedure over these vertexes, it can be decided whether specific points are inside or outside of the iso-surface. By determining which edges of the cube are intersected by the iso-surface, it is possible to create triangular patches which divide the cube into regions contained within the iso-surface and regions outside of the iso-surface. By connecting the patches from all cubes on the iso-surface boundary, it is possible to create a complete surface representation. Unfortunately, this procedure loses information of 3D model orientation and characteristic points placement which are mandatory for following processing steps.

What more, this mislaid information is crucial to prepare images mapping definition. Relative coordinates can be achieved by defining orientation points for both images (both captured from CT and ECHO). A number of these points must be given manually in order to calculate object orientation-in three dimensional (3D) model space (Fig.1A)and also in plain (2D) ECHO bull's-eye representation(Fig.1B). To achieve a balance between usability and accuracy of mapping, the number of points required for object orientation can be

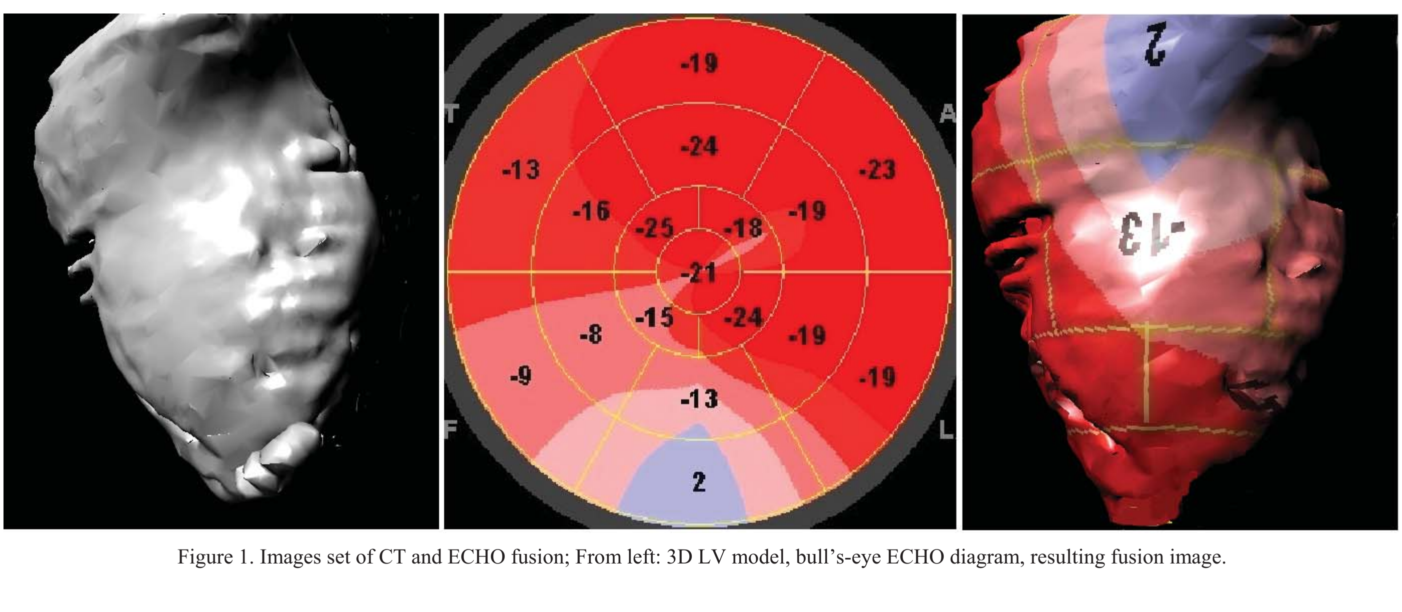

Figure 1. Images set of CT and ECHO fusion; From left: 3D LV model, bull's-eye ECHO diagram, resulting fusion image.

increased, but experimental results demonstrated that a minimum of three points have to be provided in order to handle appropriate orientation mapping accuracy. Proper quality of mapping can only be assured if the reference points are placed carefully, performed by experienced medical personnel with strong knowledge of LV anatomy. Final algorithm, which is last of sequence presented in Fig. 1C, is texturing. Custom texturing is prepared to merge those two different domain (3D and 2D) images into one interactive view. By using prepared reference points it is possible to map all points of volumetric 2D image from ECHO into 3D LV model structure (see Fig. 2). At last point of fusion procedure 3D view of coronary arteries and pericardium are added to prepare image useful for further medical investigation.

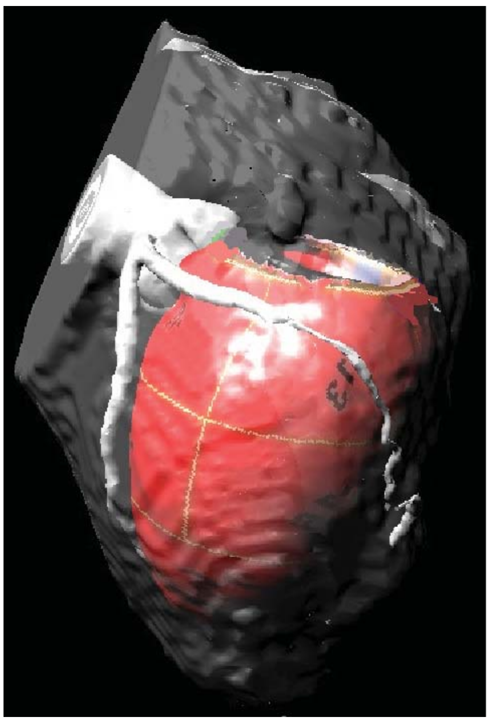

Figure 2. Final view (left ventricle, coronary arteries, pericardium) with ECHO analysis

IV. Simulation of Transesophageal Echocardiogram

One of the ultrasound based methods with great significance to the diagnostic process in cardiology is a transesophageal echocardiogram (TEE). The examination is based on inserting a USG probe into patient's esophagus for a more direct observation of the heart. The distance that the sound waves must travel to reach the heart is significantly smaller than in the case of a TTE. TEE can be used to obtain a clear view on the atria, valves, aorta or pulmonary arteries.

Although TEE provides a significant amount of imaging information and can be used as definitive way to diagnose the patient, the examination is administered only when necessary. The patient experiences a large discomfort caused by the inserted probe and may require use of sedatives or even a general anaesthesia. Additional risks such as esophagus perforation require that the examination must be carried out by a team of medical personnel, including a trained technician. These constraints render the learning process of TEE to be a challenge. The problems however may be alleviated by use of simulation methods that do not require the patient's presence, and reduce the stress level of the trainee. The paper addresses this problem by presenting a simulation setup and highlighting the some of the issues that are faced when building one.

The current state of the art in the field of ultrasound simulation can be divided into 2 main approaches. The first one is based on deep analysis of the physical phenomena that occur during propagation of ultrasound waves inside human tissue. Simulator Field II proposed by Jensen et al. [1], although accurate may not be easily used for real time simulation. The second approach typically uses a simplified model, that yields approximate, but of acceptable quality, images. Work by Sun et al. [6] uses a 3D model of human heart as a starting point, followed by plane clipping and texture mapping. Shams et al. [5] propose a use of an approach that combines both online and offline processing, where especially edge detection for simulating reflections and application of Field II for simulation of scattering maps are done in the offline phase. The authors' point that the algorithm may work in real-time producing up to 15 frames/second, however no indication of memory footprint is provided. Kuttner et al. [7] enhance the approach proposed in [5] and utilize the processing power of GPU.

The goal of the authors of this paper is to build a setup for USG simulation that can be used in a training process of medical staff. It is not crucial to provide a pixel-perfect simulation, but rather the tools and means for building a cost effective device. Ideally the setup should be like one shown in Fig. 3. The software and the data set should be optimize so that running simulation on a memory and processing power constrained devices is feasible. The communication interface is based on USB, while the mock-probe shall appear as a HID device. Due to its simplicity, the simulation method used by the authors of this paper is based on [8]. The method makes a direct use of data collected in the process of CT and the transformation is based on a simple histogram adaptation process. The transfer function can be easily fine-tuned at runtime, and its application can be easily performed with use of a LUT. Assuming a similar histogram adaptation function as the authors, the example result of pixel brightness adaptation stop for simulated USG image is presented in Fig. 4. A composition of all CT images in a sequence for one patient shows that the actual heart image is contained in only a fraction of the whole image. A more detailed view on the effective area for simulation (i.e. the area occupied by heart) is show in Fig. 5. Given the physical properties of the US, certain areas that are stored in the CT image are not needed during the simulation process. Using a segmentation algorithm, a mask that covers the heart can be extracted from CT image sequence. The plot showing the relative size of the area occupied by heart to the total image size is shown in Fig. 6. For given data sequence, the heart occupied no more than 1/3 of the total image area.

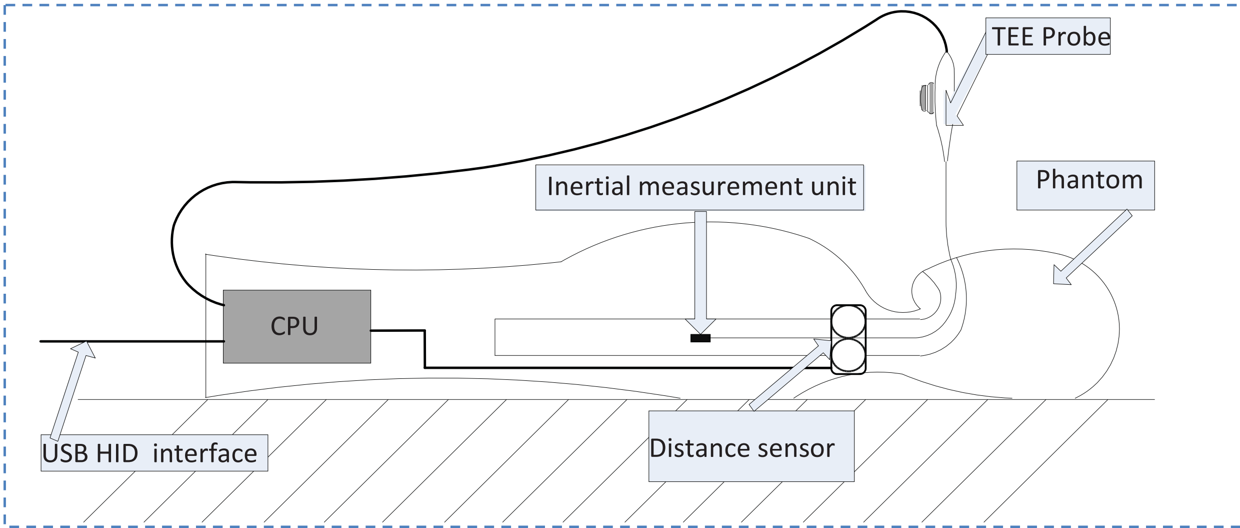

Figure 3. Block diagram of TEE simulation device.

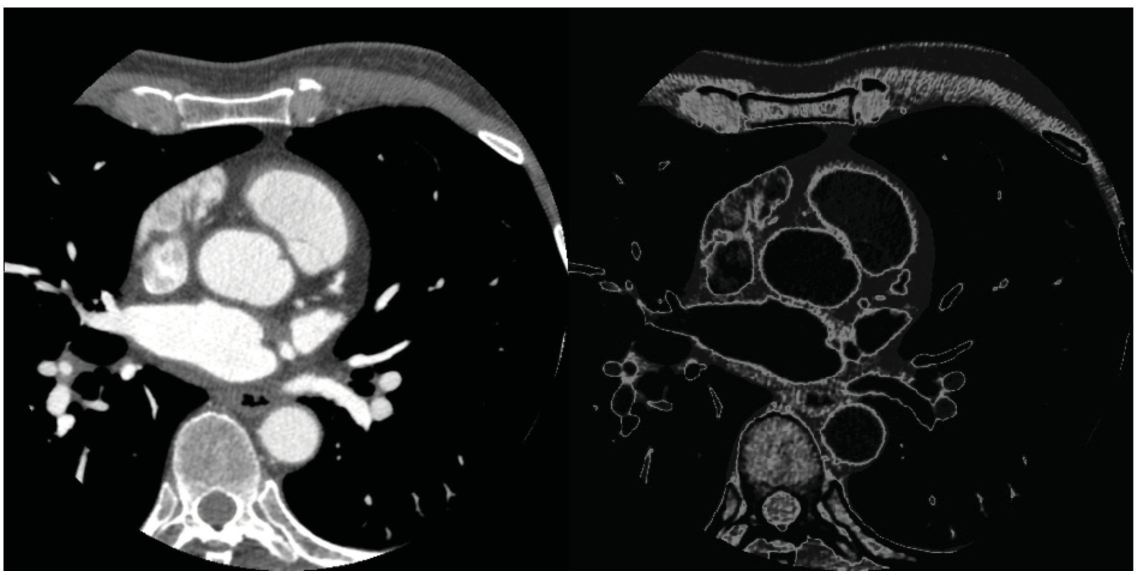

Figure 4. Side by side comparison of CT and simulated USG image

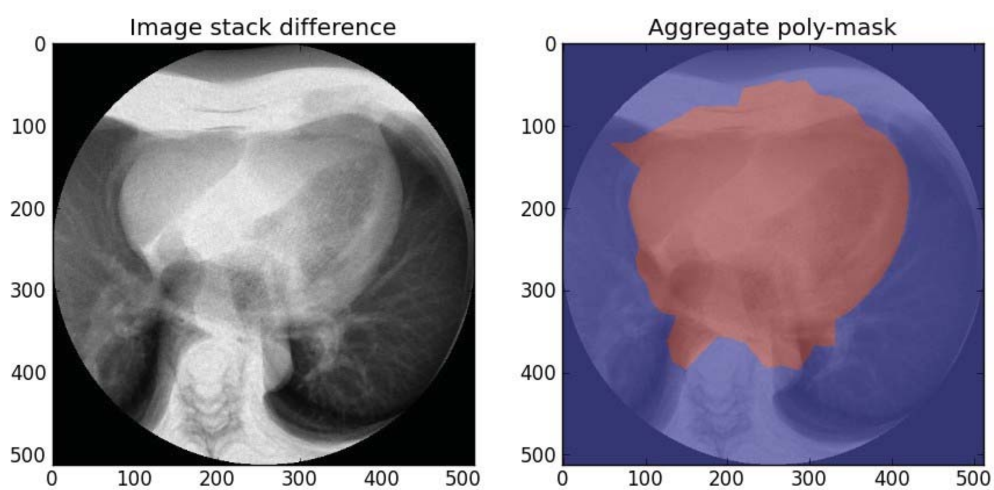

Figure 5. Example of a USG image simulated with use of brightness adaptation method.

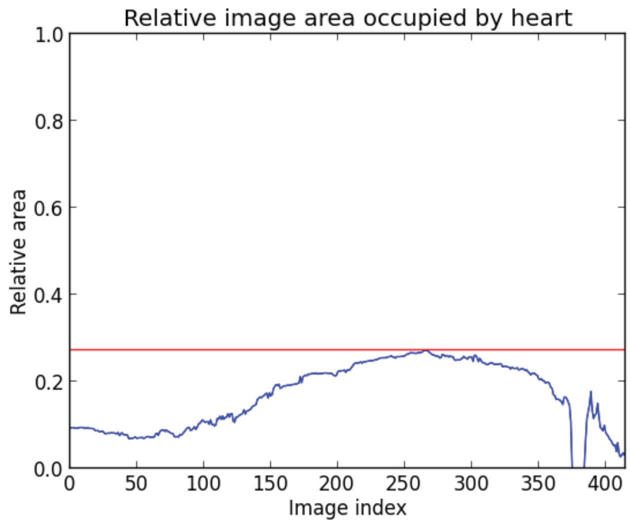

Figure 6. Plot showing a relative area occupied by heart to the whole area of image. For this purpose a set of masks for each CT slice was generated, area of each of the masks is assumed to cover the heart.

The data set under question consists of 400 0.25mm thick slices and represent a single snapshot of heart's cycle. Each image is 512x512px in size, 16bit pixel depth, accounting for 512kB of uncompressed data for a single slice. The resulting set for a single patient requires more than 200MB of storage. For purpose of animation at least 8 such data sets are required, thus severely pushing the limits of capabilities of smaller devices. By discarding the information not used in the simulation process, it is possible to obtain a significant reduction in storage requirements. Further compression to PNG format may provide additional saving, however, the image will still need to be decompressed when accessed in the TEE simulation application. In order to fit the simulator into the memory constraints imposed by small devices (typically 256MB – 1GB of RAM) a new, tailored image representation is needed.

V. Conclusions

The paper has highlighted the most significant achievements in projects which were prepared as software solutions in cardiology usage. Those projects were prepared to fulfil medical expectation and introduce new imaging processing techniques in clinical environment. New requirements and team desire to develop better and featured solutions force that presented projects will be continued and expand in close future. Work will focused on developing techniques able to automatically recognise characteristic points on heart structure to make possible fusion transformation would perform fully automatically.

Although state of the art in the topic of USG simulation is already fairly advanced, the concerns related to memory footprint, that are a result of pushing the TEE simulation software to be widely available, need to be addressed. The storage requirement may be easily addressed by use of masking and discarding the data not directly relevant to the simulation process. The run-time memory footprint however, is still too large. The authors will continue to work on determining an image representation suitable for use on memory constrained devices.

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