3D Echocardiography Powered by CNN Technology

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***Abstract* – In this paper, the first CNN [1]-[3] based experimental results in 3D echocardiography are reported. The 3D view of the human heart is reconstructed from 2D projections taken at different angles by an electronically controlled transducer. The analysis of these 2D slices (filtering, segmentation, contour tracking and content/context based recognition) is designed as an analogic CNN-UM [4] algorithm, while the 3D reconstruction (contour sub-sampling-interpolation, 3D rotation-translation, and polygonial reconstruction) from the reduced data set as a DSP algorithm. A novel CNN system has also been designed, called the ACE-BOX Analogic Computer hosting both types of the aforementioned state-of-the-art microprocessors (e.g. [5] and TI-C6x) that ideally support these computationally highly demanding experiments. The paper outlines the hardware-software and algorithmic framework of a long-term research plan providing also the first off-line simulation results.**

1 Introduction

Diagnostic algorithm concepts in pediatric cardiology have changed abruptly in the last 2 decades. Ultrasound techniques became more and more fundamental in diagnosing morphologically diverse abnormalities, since 2D imaging combined with various Doppler technologies could provide sufficient information for the clinical decision making with respect to the surgical treatment. Besides, the formal diagnostic gold standard – the cardiac catheterisation – was far more invasive, therefore it had been a strong motivation to replace it by a less harmful one.

Congenital heart diseases represent complex 3D structures which can be categorized into smaller, or larger anatomical-structural groups, but still there is a considerable variation within these groups. More importantly, those variations can deeply influence both the surgical and the catheter interventional treatment. The conventionally used diagnostic modalities are using 2D imaging. In the medical practice 3D reconstruction is usually made by the cardiologist's brain, which is highly dependent on the knowledge and experience of the examiner. In this process the reconstruction necessarily contains a number of subjective elements and can easily lead to misinterpretation. Large proportion of uncertainty arises from the improper „echo-window", meaning that structures between the echo transducer and the heart can deteriorate both the quality and quantity of the measured signal. Moreover, the complex geometric structures are seen from a different view and angle during the surgery, since the surgical approach regularly is the so-called median sternotomy (a frontal approach of the heart located in the left part of the chest cavity). The above mentioned arguments underline that there is a considerable technique-based uncertainty in visualizing those complex structures, and all these can deeply influence the effectivity of the surgical procedure, and consequently the proper treatment of the patient.

In case of a possibility to study those structures before heart surgery, precise identification of the „target" can be achieved and an appropriate surgical plan can be worked out beforehand. This will also result in a shorter duration of the surgical procedure, which obviously can reduce the complications. It is important to emphasize, that the benefit of the patient will coincide with a considerable cost-reduction of the whole treatment activity.

A 3D on-line visualization of congenital heart abnormalities along with the possibility to study them from different views, including the quantitative measurement of the heart cavities, can revolutionary change the efficacy of the treatment of congenital cardiac malformations.

2 Pediatric Cardiology

Pediatric cardiology is a small, well-defined subspecialty, which in recent years improves very rapidly. The number of survivals due to the improvement of surgical and catheter intervention techniques is significantly increased. Proper medical care of those patients with treated and untreated congenital heart diseases requires unique techniques, instrumentation and knowledge.

In the course of our experiments pediatric cardiology has been put in focus, since in this area 3D echocardiography is one of the most important and promising tools that can significantly improve the efficiency and reliability of patient treatment.

3 System Specification

The engineering specification of the system designed for 3D echocardiography (see related topics in [10]-[12]) experiments is given in Fig. 1-3. The function of the main sub-system is explained on a signal-flow graph (Fig. 1) viewing the main data flows and processing stages within the system. The hardware architecture incorporating both a CNN-UM and a DSP-type microprocessor is visualized in Fig. 2, while the main software layers are specified in Fig. 3.

3.1 Understanding 3D Reconstruction as a Signal Fusion Problem

Fig. 1 presents the reconstruction problem in 3D echocardiography as a signal fusion problem. This terming is justified by the fact that there are two types of input data flows entering into the signal processing sub-systems: (i) a 2D flow consisting of the 2D projections taken under different angles, and (ii) a 1D flow informing on the 3D position of these slices (Remark: naturally, in the actual implementation there is only a single data flow consistent with the DICOM standard). The task is to extract the relevant geometrical information from 2D projections and "fuse" it with the position information during the reconstruction. One can easily notice that though in the current experiments the position information is not a real sensory output (the position is directly controlled by the electronic system), the framework described is intended to be flexible enough to incorporate any 2D flows (e.g. CT data) completed by a 1D position data flow (sensory output or a direct control).

3.2 Hardware Architecture

The hardware architecture of the system is shown in Fig. 2 (see the ACE-BOX analogic computer). This general purpose hardware has been designed as a spatio-temporal array computer and incorporates both a state-of-the-art CNN-UM (ACE4K [5] or ACE16K) and a DSP-type (TEXAS C6x) microprocessor. The system complies with the PC104+ industrial standard. *Remark*: Fig. 1 and Fig. 2 are consistent, since in Fig. 2 the data flow is transferred directly to the CNN-UM chip (PCI Bus → Platform Bus) without being preprocessed by the DSP.

3.3 Software Layers

The main software layers of the experimental system are shown in Fig. 3. Data from the echo system is transferred in a format complying with the DICOM standard. Above the DICOM interface one can identify the major signal processing (both analogic and digital) software modules and the database handling modules. On top of these layers 3D modeling, rendering and visualization completes the software system.

3.4 The Algorithmic Framework

The analysis of the 2D slices (filtering, segmentation, contour tracking and content/context based recognition) is performed in an analogic CNN-UM [4] algorithmic framework, while the 3D reconstruction (contour sub-sampling-interpolation, 3D rotation-translation, and polygonial reconstruction) from the reduced data set exploits DSP-type algorithmic approaches.

The major processing subroutines are as follows:

Spatio-temporal nonlinear filtering (CNN-UM)

The echo images are mainly corrupted by so-called "speckle" noise inherent to coherent illumination and Rayleigh scattering caused by tissue microstructures. An optimal nonlinear reconstruction filter should approximate the mode of the local histogram.

Multiple-chamber contour tracking (CNN-UM)

After noise filtering, the contour of all visible chambers of the human heart (2 atriums and 2 ventricles) should be located and tracked in parallel in each 2D slice.

Content-context based recognition (CNN-UM)

The visible chambers should be detected and marked (context based analysis), the chambers should be analyzed individually in order to discover the regional abnormalities (content based analysis).

Contour sub-sampling and interpolation (DSP)

Sub-sampling and interpolation of the chamber contours using a curvature adaptive methodology.

3D rotation and translation (DSP)

Linear transformation of the "smoothed" contours based on the information extracted from the 1D position flow.

Polygonial reconstruction (DSP)

Polygon based reconstruction of the 3D model with a dynamic feedback to previous processing subroutines (contour tracking and sub-sampling) in order to adaptively correct the errors introduced in these phases.

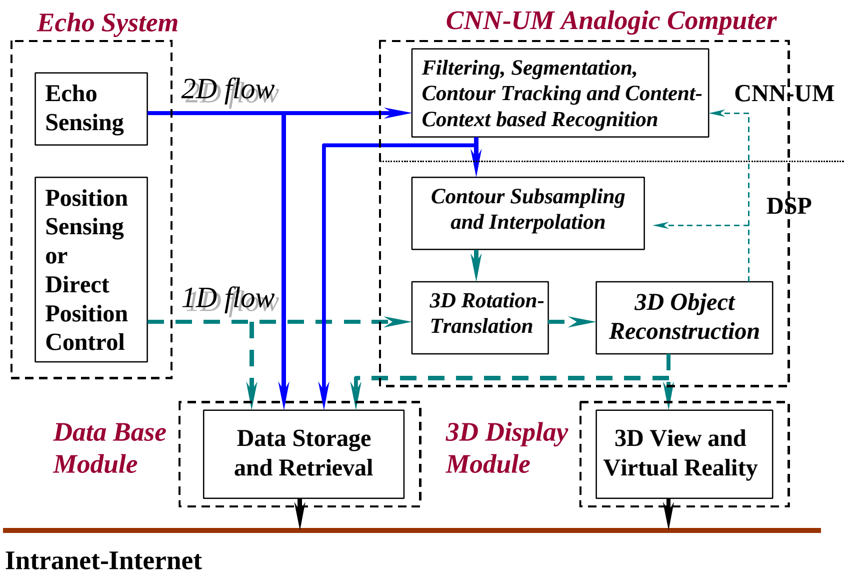

Figure 1 *System specification: signal flow diagram*

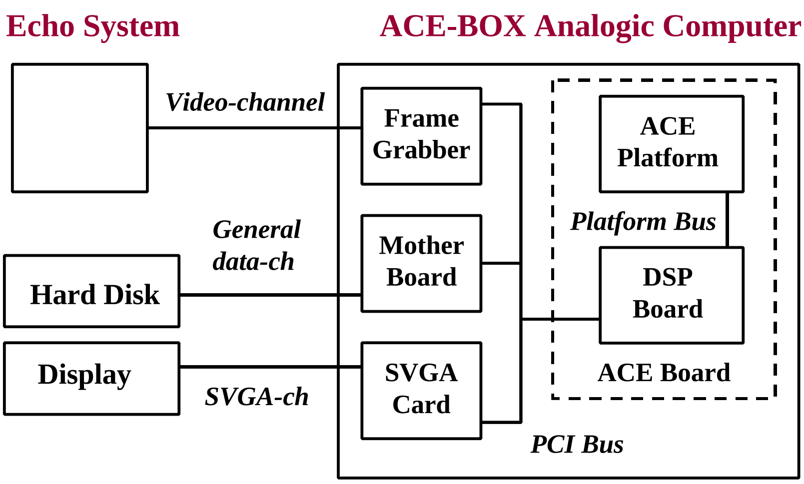

Figure 2 *System specification: hardware architecture*

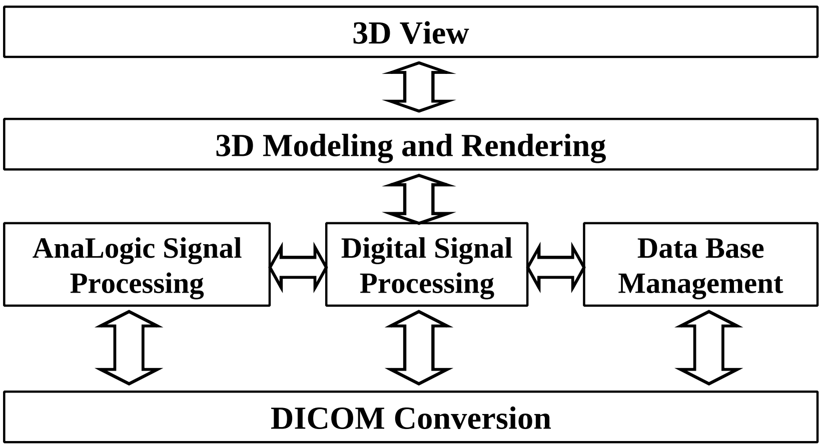

Figure 3 *System specification: software layers*

4 Experimental Results

The main hardware-software components of the ACE-BOX Analogic Computer have already been been developed (a CNN-UM chip [5] and a DSP-type microprocessor /C6x/ are operational within the system). The algorithm design, implementation and optimization is an on-going research.

Currently, these experiments incorporate a dozen video-flows of different patients. The data is analyzed off-line through computer simulations in order to test the algorithms before a full system integration.

4.1 Working Method

The cardiology specialists of our team support the experiments by semi-automatically tracking the borders of different chambers on all 2D projections. This way a “ground-truth” data is created validating the performance of the CNN based segmentation and tracking algorithms (trigger-wave based active contour tracking [6]-[9]) and this method also creates reference data for the DSP-based 3D reconstruction experiments.

4.2 Simulation Results

Off-line simulation results are shown in Fig. 4 visualizing a full 3D reconstruction output.

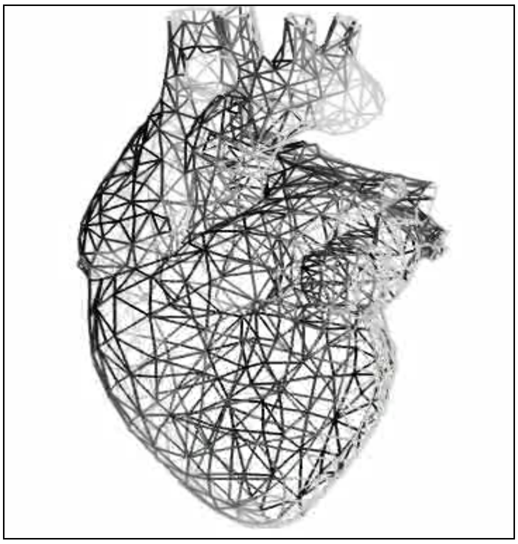

Figure 4 *Output of the 3D reconstruction algorithm: a full 3D model of the human heart.*

5 Conclusions

We have described a 3D echocardiography system powered by CNN technology. Both the hardware and software specifications were given along with the explanation of the main processing stages. Though the development and optimization of the system and related algorithms is an on-going research, the first off-line simulation results were also shown: a full 3D reconstruction from a sequence of 2D projections.

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