Integration of Multiple Sensor Modalities in ActiveVessel Cardiology Workstation

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***Abstract*—ActiveVessel is a new multimedia workstation which enables the visualization, acquisition and handling of different medical image modalities on- and offline for cardiology purposes. It implements DICOM v3.0 decompression and browsing, video acquisition, reproduction and storage for IntraVascular UltraSound (IVUS) and angiogram analysis. A distinctive implementation feature is the automatic catheter segmentation in angiography images. Another distinctive feature is the interactive mode of model correction via mouse dragging. A third and novel technical solution of the catheter path reconstruction is the integration with a magneto-sensitive micro-device inside the catheter for faster and safer minimal invasive surgical intervention. The paper gives the overview of the entire system, its basic new functionalities and the proposed technical solution of integration of four (instead of three) sensor modalities in cardiovascular practice.**

***Index Terms*—cardiovascular diagnosis, angiogram and intravascular ultrasound analysis, multimedia, catheter path reconstruction, magneto-sensitivity**

I. INTRODUCTION

The new multimedia workstation ActiveVessel possesses essential multi-functionalities in assisting cardiologists and specialists in minimal invasive cardiological surgery. It is designed in cooperation with cardiologists from University Hospital Germans Trias i Pujol to help them in the diagnosis and storage of all the data relevant to each study, thus speeding up the process of evaluation and the treatment of coronary lesions. Moreover, it supports mental conceptualization of the vascular disease when data and images are acquired from several sensor modalities, none of which contains the complete information about the vascular disease. The overall structure of the new multimedia workstation is shown on Fig. 1. The details of a new 3D silicon magnetometer with simplified structure and its advantages and role in minimal invasive surgery are presented. The paper outlines some of the image analysis solutions in ActiveVessel and the conclusion section discusses future enhancements of the system.

Our objective is to develop a new tool for hospitals using IVUS and angiography for on- and off-line evaluation of stenosis, stent implantation and balloon treatments. In many instances of medical practice this data fusion process makes emerge new information that would not have been easily deduced from each image or signal modality by itself. In particular, our aim was to create a new application to fuse the information coming from the angiographic and the intravascular ultrasound equipments. This objective has lead us to the creation of ActiveVessel workstation which incorporates multimedia capabilities as video and audio acquisition, reproduction and storage of angiograms and IVUS images with their corresponding ECG signal and magneto-sensitive tracing of the path of the catheter. It also handles relevant information/knowledge about the patient and the study.

II. FUNCTIONALITIES OF ACTIVEVESSEL

A. Managing IVUS, Angiogram and Magnetic Data

A DICOM v3.0 decompressor and browser is implemented to manage angiographic data. ActiveVessel is capable to record and handle more than 3000 IVUS images of 456x456 pixels with a frame rate of 25fps with their correspondent ECG data sampled at 10MHz (without loss) on an Intel Pentium III 866MHz dual processor with 512Mb of RAM with Microsoft Windows 2000 Professional. It is equipped with Euresys Piccolo video capture card and an integrated SoundMax audio capture card (for ECG). These represent more than 6 cm pullback at constant pullback speed of 0.5mm/sec.

ActiveVessel has implemented several essential system capabilities, such as the automatic segmentation method for catheter visualization in the angiographic images and 3D visualization of vessel layers (extracted from the IVUS information), incorporating tortuosity coming from the angiographies, in OpenGL. It defines the real 3D distance between two certain points in the vessel or referring to a bifurcation area between vessel layers, leading to exact correspondence between IVUS (in long- and short-axis view) and angiographies.

One of the current development lines of ActiveVessel is integration with a magneto-sensor for precise 3D positioning of the catheter to simplify the image acquisition protocol. For this purpose, silicon micro-transducers can be

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applied, functioning on the basis of the Hall effect and the magneto-transistor and magneto-diode effects [1], [2]. Based on these effects 2D and 3D micro-systems of about 1mm size are manufactured. They contain, along with the sensor, components of the electronics that process the data. These micro-devices are with enhanced precision of processing information while substantially reducing the parasite noise. To achieve this, the new micro-sensors are with parallel axis of sensitivity [1]. All this makes them appropriate to implement in medical applications.

In order to function usefully in minimal invasive surgery the magnetic sensor micro-device needs a generator of magnetic field (e.g. located on the image intensifier). The motion of the catheter with the magnetic sensor inside the vessel initializes the useful information via the magneto-sensitive output signal in the presence of magnetic field. In [2] the idea for implementation of magnetic field sensors inside catheters has been theoretically justified, however without any possible implementation due to the large size of the used sensors as well as of the combination of 1D and 2D sensors. The signal processing electronics was also a standard one, and not integrated in the sensor chip. Our solution is new and original one – it integrates sensor and processing in one and the same chip, its construction is simplified with reduced number of contacts and it allows 3D-sensor position registration with very high precision.

B. "Chronology" of ActiveVessel Functionalities

1) On-line Processing

ActiveVessel has a wide range of capabilities that will be explained chronologically from the moment the physician turns it on. The flowchart of the entire system is given in Fig. 1.

As soon as the application starts up the physician decides if s/he wants to start working online or offline. In the online process, the first thing needed is the information about the clinical case and the patient, which is retrieved by filling a form. After this set up process, a set of images is provided. To reconstruct the IVUS catheter path from the angiographies the Dumay's method is used [3] with the (un)distortion corrections proposed in [4] so we need two pairs of angiographic series at the pullback beginning and another pair of them at the end. In [5] we present an acquisition protocol to assure the minimal error possible in the reconstruction of the path covered by the IVUS catheter during its pullback along the vessel. It consists of five steps:

a) Choose two optimal views (minimum foreshortening) of the catheter with an angulation between both projections greater than or equal to 30 degrees [3], avoiding to change the distance between the intensifier and the isocenter (OC).

b) Acquire the first projection with the catheter stopped at the beginning of the pullback, asking the patient to keep the breathing to avoid displacement during the sequence.

c) Acquire the second projection without changing the OC and avoiding the use of saved positioning (large mechanical error).

d) Do the pullback of the IVUS catheter without moving the C-Arm.

e) Acquire two more projections with the catheter stopped and the pullback's end following steps 3 and 2.

2) Off-line Processing

Video and ECG recorder. To perform this acquisition protocol the workstation is equipped with a real-time video and ECG acquisition module consisting in an Euresys video capture card and a SoundMax sound card. A video output of the angiographic equipment, containing the same information shown on the laboratory monitors, is used as an input for the system. A region of interest (ROI) of 512x512 containing the angiography is defined on the input signal to accelerate the storage process.

For the ECG signal acquisition, we use the workstation sound card with a voltage and current attenuator to avoid over-saturation. Given that the sound card works as a band-pass filter, the input signal has to be integrated in a sliding window in order to recover its original shape. Once we have the ECG recovered and the angiographic images recorded, we automatically select the angiographies corresponding to the end of the S curve of the ECG to assure maximum ventricular volume [6]. The same recording procedure is taken for the IVUS data. In this case, the ROI selected is of 456x456 pixels and the frame rate is 25 fr/sec.

Off-line processing. The application also incorporates a DICOM CD browser to permit the analysis offline for angiographic and IVUS data. This browser presents a list of all the studies contained in the CD and the user is able to select the needed one.

In case of off-line processing, the information about the study and the patient is extracted automatically from the data contained in the DICOM. Once the desired study is selected, a series browser is presented with relevant data about the clinical case. Each series can be played with common video player options. In the case of IVUS data the images are loaded as a bitmap sequence, only providing to the system information about the used frame rate and the distance (in millimetres) between two consecutive grid marks in the IVUS image. Whether the images have been acquired directly using the recorder module, or loaded directly as a bitmap sequence, a new module of the application permits to define closed models of the vessel layers as closed B-Splines [7].

Fusion process. X-Ray images are characterized with low signal-to-noise rate. Therefore, the fusion process has to begin with local enhancement of the angiographic image to help in the catheter segmentation following the fast marching algorithm in a surface of minimal action computed in both angiographic projections of the IVUS catheter [7]. The complete procedure of enhancement and segmentation is explained in [5]. The segmented catheter is placed in the space following the methodology proposed in [3] and the steps are explained in [8]. The method consists in establishing a global reference system with its origin in the isocenter of both image projections.

This global system permits the establishing of exact correspondence between the segmented catheter paths of both projections. It recovers the real 3D path the catheter has followed during its pullback inside the blood vessel. The image fusion process leads to exact correspondence between IVUS and angiograms.

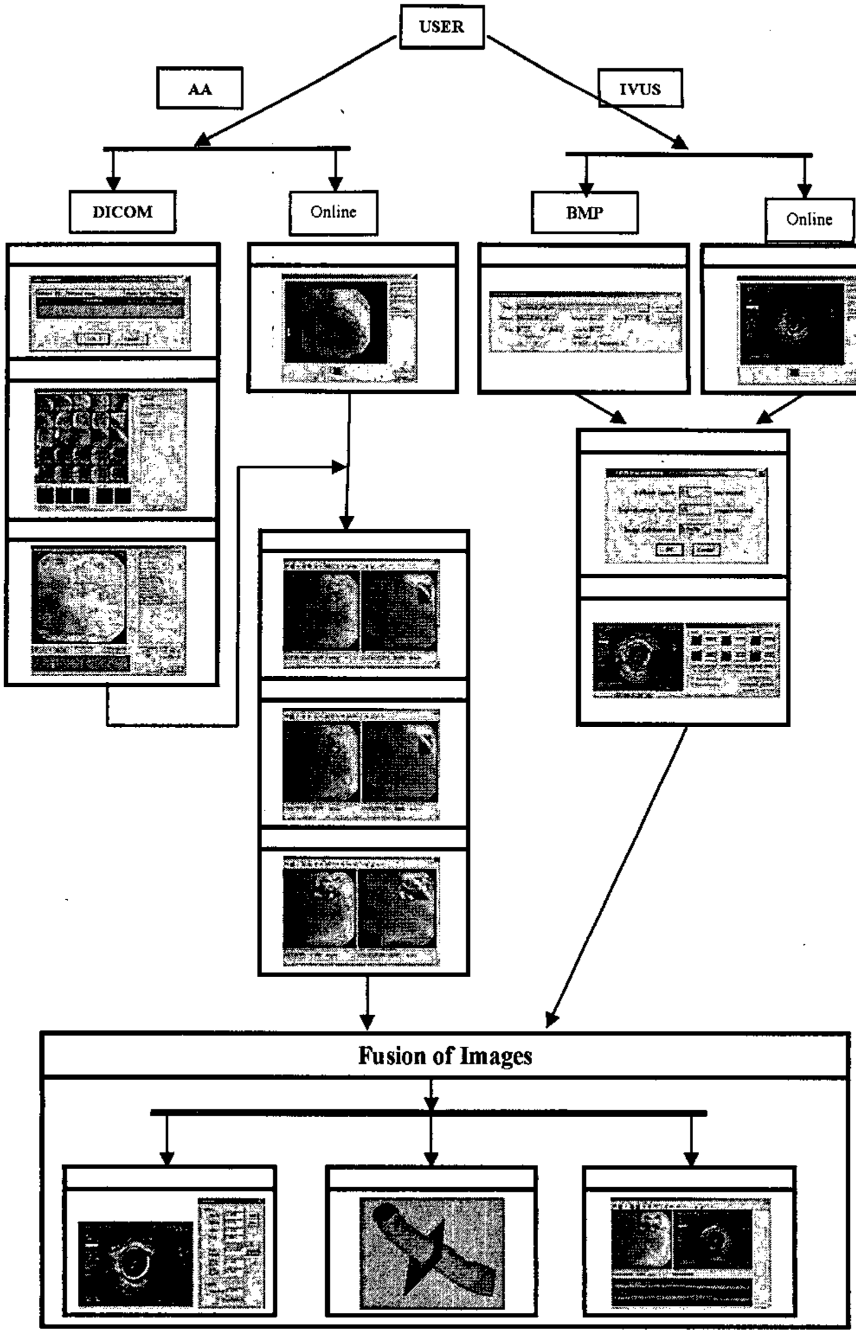

Fig. 1. ActiveVessel flow diagram.

The exact correspondence is established by measuring the reconstructed path length in 3D. This is the main module of the application, involving direct interaction between the physician and the resulting image modalities at one and the same time.

Taking into account that we have the ECG not only for angiograms, but also for the IVUS cube of images, the images corresponding to the same cardiac cycle in each of the image modalities are selected. In this way the imprecise calculus of the IVUS image position along the recovered path curve is avoided. This procedure is similar to ECG-gated acquisition, but instead of stopping the catheter pullback waiting for the next ECG pick, the application records all the pullback non-stop and permits viewing all the images of the pullback, determining its position depending on the corresponding cardiac cycle.

The application shows a dialog containing one of the angiographies of the studied vessel, the IVUS image corresponding to the point selected in the angiography and a long-axis view of the IVUS stack of images. Currently we are working on including a precise intensifier localiser – 3D micro-magnetometer - that will permit the physician to change the OC distance between both projections and also to track the catheter position during the positioning of the intensifier, accelerating the acquisition and the catheter detection.

C. The New Silicon-based 3D Magnetometer

1) Micro-Device Structure

The device design of the new integrated 3D Hall sensor is shown on Fig. 2. It uses the first parallel-field Hall element, devised in 1983, which has three n^+ contacts. Despite of its simplicity, this micro-transducer has characteristics and performance, which are as good as those of all four-contacts, five-contacts, six-contacts and other parallel-field Hall modifications created until now [1]. On the one side of the n-Si substrate, five n^+ contacts are formed – one central C_0 with square form and four strip contacts C_1, C_2, C_3 and C_4 placed at equal distances from the four sides of C_0. A deep p-well ring with square form, which repeats the device symmetry, implements the vertical boundaries and restricts laterally the active sensor zone in the bulk of the substrate. The contacts C_1-C_0-C_2 and respectively C_3-C_0-C_4, the energy supply E_n and the load resistors R_1 - R_2 and R_3 - R_4, define two functionally integrated triple parallel-field Hall elements with common contact C_0, oriented one towards another on 90°. The sense contacts are the simultaneously supply ones.

2) Micro-Device Operation

The action of the 3-D integrated Hall sensor is the following. At supply $E_n > 0$ and as a result of the symmetry of the transducer, within the active region there are four bias currents which are two by two with opposite direction, i.e. $|I_{C0,C1}| = |-I_{C0,C2}|$ и $|I_{C0,C3}| = |-I_{C0,C4}|$.

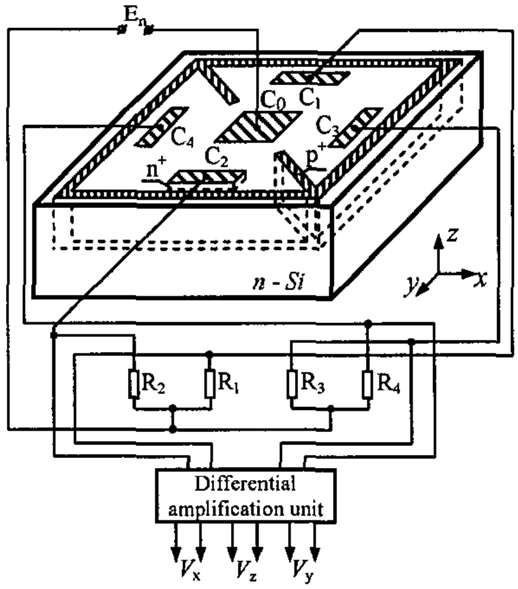

Fig. 2. 3D silicon-based magnetometer with simplified structure and enhanced sensitivity.

The sum of these components is equal to the current I_{C0} via the central contact C_0. The mid-cross-section in y-z plane and the current lines of the triple (C_1-C_0-C_2) Hall sensor are shown in Fig. 2. The picture for the other Hall element C_2-C_0-C_4 is the same. Through direct measurement of the Hall voltages $V_x(\boldsymbol{B}_x)$ and $V_y(\boldsymbol{B}_y)$ at current I_{C0} = const., we obtain the full information about the two components $\boldsymbol{B}_x$ and $\boldsymbol{B}_y$. The operation principle being used and the high degree of symmetry of the device eliminate any $\boldsymbol{B}_z$- field influence in x- and y- channels.

It is of interest the sensing of the orthogonal to the device surface $\boldsymbol{B}_z$- component. The Lorentz deflection of the currents $I_{C0,C1}$, $I_{C0,C2}$, $I_{C0,C3}$ and $I_{C0,C4}$ in x-y plane at Hall angle $\Theta_H = \mu \boldsymbol{B}_z$ leads to generation of Hall potentials with the respective signs on all four contacts C_1...C_4, i.e. half of the Hall voltage $V_z(\boldsymbol{B}_z)$. is developed on them. Thus, the full Hall voltage $V_z(\boldsymbol{B}_z)$ is generated between the pairs of contacts C_1-C_3, C_1-C_4, C_2-C_3 and C_2-C_4. The output signal $V_z(\boldsymbol{B}_z)$ of the $\boldsymbol{B}_z$- channel represents the differential voltage between two neighbouring contacts C_1...C_4. This is possible because the sensor zone is separated appropriately into two equal parts through the p-well ring. In order to extract the net Hall voltage $V_z(\boldsymbol{B}_z)$, it is necessary to express the signal $V_z(\boldsymbol{B}_z)$ by a simple combination of voltages, generated by $\boldsymbol{B}_x$, $\boldsymbol{B}_y$ and $\boldsymbol{B}_z$ between each one of the four contacts C_1...C_4 and the common device center point. Such a neutral point is the central contact C_0. In our case, for these voltages the following relation holds $V_z = (V_{C1} - V_{C3} + V_{C2} - V_{C4})/2$. This operation is easily implemented in hardware circuitry by the use of two double instrumentation amplifiers. Two op-amps serve for conditioning of the Hall voltages V_x and V_y, and the other two op-amps implement the relation for obtaining the net Hall voltage $V_z(\boldsymbol{B}_z)$. The high device symmetry and the technological lateral confinement overcome the channel cross-sensitivities and make it suitable for medical instrumentation.

D. Conceptual ActiveVessel Functionalities

Three-dimensional visualization. The fusion of IVUS with angiographies combined with the two-dimensional models of the vessel layers defined on the IVUS images has permitted the visualization of these models with their tortuosity in 3D. The way of placing the models along the 3D curve corresponding to the IVUS pullback is by orienting the X- and Y-axis of the IVUS image with the normal and binormal of the curve, respectively [9]. This allows transforming the 2D curve models to a 3D Non-Rational B-Spline (NURB) surface in OpenGL.

Interactive Features. As it was mentioned, a crucial point in the image reconstruction algorithm is the initialization of the model in noisy environment. In following the catheter path, the model may diverge from the true path. The physician can, interactively, drag the "model" (the curve) to approximate the true position of the catheter. The catheter path is corrected, thus minimizing computation and error cost.

E. Further Development of ActiveVessel

Currently, catheter path definition via multiple sensor modalities is studied, to improve precision and reduce the amount of angiograms needed.

Tissue characterization is another problem to be studied. Combining the three-dimensional placement of the IVUS data with the tissue characterization will allow performing automatic diagnostics of the vessel pathologies. The dialogue with the cardiologist can be more flexible and with enhanced semantics. ActiveVessel is compatible with Internet-based technologies for remote access to image database.

III. CONCLUSIONS

We have presented ActiveVessel - a new multimedia medical workstation, which enables the visualization, acquisition and handling of different medical image modalities on- and offline. Among its multiple functionalities are automatic catheter segmentation in angiography images, interactive model correction, and 3D visualization. The paper has emphasized the new technical solutions in ActiveVessel, and in particular the integration with a magneto-sensitive micro-device inside the catheter for path reconstruction based on four (instead of three) sensor modalities. This makes ActiveVessel unique and implementable in cardiovascular practice.

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