Multimodal Data Fusion for Intelligent Cardiovascular Diagnosis and Treatment in the ActiveVessel Medical Workstation

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ABSTRACT

ActiveVessel is a new multimedia workstation that enables the visualization, acquisition, and handling of different medical image modalities on- and off-line for cardiology purposes. The workstation implements image decompression and browsing, video acquisition, reproduction, and storage for intravascular ultrasound (IVUS) and angiogram (X-ray) analysis. A distinctive implementation feature is the automatic image reconstruction with intensive use of 2D and 3D deformable models (snakes). The interactive interface allows the user to ‘correct’ deviations of catheter path reconstruction. An important characteristic feature of ActiveVessel is the interactive mode of model correction via mouse dragging. A novel technical solution for catheter path reconstruction is the integration with a magneto-sensitive micro-device (MSMD) inside the catheter/vessel for faster and safer minimal invasive surgical intervention. This paper gives the overview of the entire system, its basic new functionalities, and the proposed technical solution of integration of four sensor modalities in cardiovascular practice.

KEYWORDS

angiogram and intravascular ultrasound analysis, multimedia, catheter path reconstruction, magneto-sensitivity

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1. INTRODUCTION

A new multimedia workstation called ActiveVessel possesses essential multi-functionalities in assisting cardiologists and specialists in minimal invasive transcatheter interventional cardiology. This workstation is an advanced tool for medical image visualization, employing algorithms for medical image analysis based on the intensive use of 2D and 3D deformable models (‘snakes’) (e.g. Cohen & Kimmel, 1997). ActiveVessel was designed in cooperation with the cardiologists from the University Hospital “Germans Trias i Pujol”, Barcelona, to help them in the diagnosis and storage of all the data relevant to each patient, thus speeding up the processes of evaluation and treatment of coronary lesions. The medical workstation supports the mental conceptualization of the vascular disease when data and images are acquired from several sensor modalities, none of which contains on its own the complete information about the vascular disease.

The objective of designing ActiveVessel has been 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 enables new information to emerge that would not have been easily deduced from each image or signal modality by itself. ActiveVessel is a new application designed to fuse the information obtained from angiographic and intra-vascular ultrasound equipment. The workstation incorporates multimedia capabilities —video and audio acquisition, reproduction and storage of angiograms and IVUS images with their corresponding ECG signals and magneto-sensitive tracing of the path of the catheter. The application also maintains a database of relevant information/knowledge about the patient and the medical case (Figure 1).

The need for integration of the magnetic modality has been emphasized by interventional cardiologists as one of the urgent technical solutions, awaited in transcatheter interventional cardiology:

“One of the most exciting technologies now being perfected is the use of magnetic navigation of wires and catheters. The technology may make X-ray guidance obsolete. The hope is that using MRI, you can map the coronary tree; then using magnetic navigation, control and advance the tip of the guidewire and catheter” (Hacim, 2004).
Fig. 1: ActiveVessel function flow diagram
The proposal for the integration of the microsensor for magnetic field into the catheter focuses on the alternative to the mainstream and costly recent medical technology solutions. Being of more than 20 years since invention and undergone numerous patents and experimental validations, the idea is of implementing smart and low-cost technical devices of comparable-to-superior parameters like simplified structure, smaller size, and higher fidelity. Devices of this kind are still under construction in the leading technological centers.

Recently, Ascension Technology announced its newest medical tracking device—3D Guidance—for transcatheter cardiovascular intervention (Scully, 2006). The commercially available device is a 1.3 mm sensor integrated into the catheter. 3D Guidance tracks the position and orientation of one or more tiny sensors, enabling real-time guidance of medical instruments for minimally invasive, image-guided procedures. Ascension is currently developing new applications for 3D guidance of catheters with its medical partners such as Cedara Software. One difference from Cedara, for example, is that ActiveVessel, as a medical visualization tool, has been designed especially for cardiology in close cooperation with the medical staff, accounting for the cognitive preferences of the cardiologists. The parallel exploration of ideas and technical solutions can contribute to the invention of optimized, low-cost, smart medical devices for wider availability of high quality health care.

This paper outlines the intelligent system solutions in ActiveVessel and the main image processing functionalities of the workstation. The contribution of the paper is the presentation of a currently developed system for cardiologic assistance designed in collaboration with the actual users of the system—the cardiologists—and the smart solutions accompanying its development.

2. CONCEPTUAL AND STRUCTURAL SOLUTIONS IN ACTIVEVESSEL

Conceptual solutions are the extensive implementations of image segmentation techniques of continuum nature and handling the problems of the excessive features in each of the image modalities. The structural solution is the implementation of a new silicon-based microsensor for wire and catheter guidance. These are areas characterizing the integrity of ActiveVessel cardiology workstation as an intelligent diagnostic tool.
2.1 The ‘Snake’ Methodology for Image Segmentation and Reconstruction

Powerful image segmentation techniques are the so-called deformable models (or snakes) (Kass et al. 1987). Snakes are especially applicable in medical imagery because of their ability to interpret sparse sets of image features (e.g. edge points, region-based descriptors, etc.) and link them in flexible image contour shapes (Cohen & Kimmel, 1997; Guyton & Hall, 2002; Cañero et al. 2002). A snake is an elastic curve that evolves from its initial shape and position resulting from the combined action of external and internal forces. The external forces ‘push’ the snake toward features of the image, whereas the internal forces model the elasticity of the curve. In parametric terms, the snake is a curve \( u(s) = (x(s), y(s)) \) where \( s \in [s_0, s_{N-1}] \) and \( (s_0) = (s_N) \) for closed curves. The internal energy is defined as:

\[
E_{\text{int}}(u) = \int \alpha \| u_s \|^2 ds + \int \beta \| u_{ss} \|^2 ds
\]

The first term is called membrane energy and defines the resistance of the deformable model to stretching. The second term is called stiffness energy and defines the resistance of the model to bending. The subscript in Eq. (1) denotes differentiation with respect to \( s \).

The external energy is generally defined from a potential field \( P \):

\[
E_{\text{ext}}(u) = \int P(u(s)) ds
\]

A typical potential field for a snake attracted to image edge points is given by:

\[
P(u(s)) \propto -\left| G_\sigma * \nabla I(u(s)) \right|
\]

where \( I(u) \) is the intensity value of the image pixels and \( G_\sigma \) is a Gaussian smoothing function of scale \( \sigma \). In general, the potential must define a surface for which minima correspond as closely as possible to the image features of interest. The total energy of the snake is the sum of the external and internal energies:

\[
E_{\text{snake}}(u) = E_{\text{int}}(u(s)) + E_{\text{ext}}(u(s))
\]
The solution to the problem of detecting a contour is obtained by minimization of the energy function, which is generally performed using variational principles and finite difference techniques. The snake with the smallest energy corresponds to the desired vessel contour. One of the important issues is how to define the image descriptors that attract the snakes. For the present system, a statistic-deterministic approach to learn vessel borders has been developed and applied. For details, the reader is kindly referred to Gil et al. (2006).

2.2 Reconstruction of the Stent and the Vessel Wall

An example of snake plasticity is the application of a deformable cylinder to a segment and the reconstruction of the stent and the vessel wall from an IVUS images stack, instead of the classical approach of segmenting 3D image volumes slice by slice. The advantage of this approach is mainly in its robustness that stems from the internal energy, which takes into account the coherence between the image planes (Figure 2). Several measurements are applied to estimate the quality of the stent deployment by the IVUS criteria defined in Robert and Safian (1998), which have three parameters: cross-sectional area (CSA), apposition, and symmetry. The ratio of

![Fig. 2: Control points defined to make knots coincide with image planes](image-url)
the minimal CSA of the stent to the normal reference vessel CSA (the average CSAproximal and distal to the stent) should be greater than 0.8. The maximum gap between the stent and the vessel wall should not be greater than 0.1mm (apposition). The ratio of the stent minor axis to the stent major axis should be at least 0.7. The parameters are obtained plane-by-plane and are accessible to the physician in terms of numerical data.

For the apposition case, a color-coded distance map is offered for a comprehensive interpretation of the stent deployment in the current plane (Figure 3). The color of each pixel indexes the distance between the two shapes in color-spectrum terms, where blue is the closest distance and red is the furthest distance. The maximum value (the brightest-red pixels) denotes the biggest gap between the vessel and the stent. The color-coded distance map is one of the original ways of representation of IVUS data in ActiveVessel. The intensity of the ultrasound images correspond to the penetration ability of the ultrasound signal interacting with the coronary tissue. The higher the opacity of the tissue the less the penetration of the ultrasound signal hence, the brighter the region in the image. We used this fact to find the vessel borders. Color-map coding has been requested by the physicians for improving their fast exploration of bad apposition of stents and high accumulation of coronary plaques.

Once obtained, the B-Spline curves that represent the vessel and stent boundaries are interpolated in space using B-Spline surfaces to construct a spatial model of the

Fig. 3: Color-coded distance map of the mutual position of the stent and the vessel wall
vessel and the stent, taking into account the pullback speed (the distance between planes) and the 2D control points (Cañero et al. 2002).

Extracting volumetric information is important to evaluate the intervention effects. Usually, area and distance calculus in IVUS planes are the only possible ones carried out with IVUS images. Having a B-Spline representation of the vessel and the stent, the distance between them is estimated using a filling algorithm (Y-X, for example) in the images with drawn vessel and stent models. The area of each model is calculated in pixels and the intersectional area $(s)$ is inferred as:

$$s = c^2_H * (a_v - a_s)$$  \hspace{1cm} (5)

where $c_H$ is the horizontal calibration and $a_v$ and $a_s$ are the vessel and the stent areas, respectively. The area calculus is extrapolated using trapezoids to get the volumetric measurement as follows:

$$V = \frac{|s_i - s_{i+1}|}{2} |c_v$$  \hspace{1cm} (6)

where $c_v$ is the vertical calibration defined by the pullback speed (the distance in millimeters between two images), and $s_i$ and $s_{i+1}$ are the intersectional areas of two consecutive planes. Consequently, cardiologists have a tool to explore the real extension of the coronary disease not in an image or a sequence, but in space as well as to measure its effect more accurately. Currently, the system is under clinical validation, extracting information from a large series of patients and comparing previous results with new ones to estimate the importance of volumetric vessel measurements. A natural extension of this work includes creating a virtual reality environment for realistic navigation and interaction with the vessel, simulating vessel interventions and implementing the automatic correction of the vessel rotation and automatic segmentation of the vessel layers.

2.3 Intelligent Microsensor Navigation Solutions

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 applied, functioning based on the Hall effect and the magneto-transistor and magneto-diode effects (Roumenin, 1994; 2003). Based on these effects, 2D and 3D micro-systems of about 1 mm in size are manufactured. The micro-systems 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 microsensors are with parallel axis of sensitivity. All this makes them appropriate to implement in medical applications.

3. ‘CHRONOLOGY’ OF ACTIVEVESSEL FUNCTIONALITIES

3.1 On-line Processing

In the case of on-line processing, the information about the clinical case and the patient is retrieved from the image database by filling a form. To reconstruct the IVUS catheter path from the angiographies, Dumay’s method (Dumay et al. 1994) is used with the (un) distortion corrections proposed in Cañero et al. (2002). Two pairs of angiographic series at the pullback beginning and another pair at the end are necessary. The image acquisition protocol follows five steps to assure the minimal possible error in the reconstruction of the path covered by the IVUS catheter during its pullback along the vessel. At step one, two optimal views (minimum fore-shortening) of the catheter are chosen with an angulation between both projections $\geq 30$ degrees to avoid changing the distance between the intensifier and the isocenter (OC). At step two, the first projection is acquired with the catheter stopped at the beginning of the pullback, asking the patient to keep breathing to avoid displacement during the sequence. Step three is acquiring the second projection without changing the OC and avoiding the use of saved positioning (large mechanical error). At step four, the pullback of the IVUS catheter is done without moving the C-Arm. Finally, two more projections are acquired after pullback end, following steps three and two.

3.2 Off-line Processing

The workstation is equipped with a real-time video and an ECG acquisition module. A video output of the angiographic equipment, containing the same infor-
mation shown on the laboratory monitors, is used as an input for the system. A region of interest (ROI) of $512 \times 512$ pixels containing the angiography is defined on the input signal to accelerate the storage process. Once the ECG is recovered and the angiographic images recorded, the angiographies are selected automatically corresponding to the end of the S curve of the ECG to assure maximum ventricular volume. The same recording procedure is taken for the IVUS data.

The application incorporates a DICOM CD browser to permit the analysis off-line for angiographic and IVUS data. The browser presents a list of all the studies contained in the CD, and the physician can select the needed one. In the 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 millimeters) 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 the definition of closed models of the vessel layers as closed B-Splines.

3.3 Fusion Process

The X-Ray images are characterized with low signal-to-noise rate. The fusion process begins 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. The method consists of 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 (Figures 4a-4b).

The system recovers the real 3D path the catheter has followed during its pullback inside the blood vessel. The image fusion process leads to exact correspondence, established by measuring the reconstructed path length in 3D, between IVUS and angiograms. This is the main module of the application, involving direct interaction between the physician and the resulting image modalities concomitantly. Images corresponding to the same cardiac cycle in each image modality are selected in such a way to avoid the imprecise calculus of the IVUS image position along the recovered
Fig. 4: Automatic segmentation of (a) 2D vessel borders for evaluation of stenosis; (b) 3D vessel reconstruction from angiography and IVUS data

path curve. 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 localizer—3D micro-magnetometer—that will permit the physician to change the OC distance between both projections and to track the catheter position during the positioning of the intensifier as well, thereby accelerating the acquisition and the catheter detection.

4. THE NEW SILICON-BASED 3D MAGNETOMETER

To function usefully in minimal invasive surgery, the magnetic sensor micro-device requires a generator of a 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 Tanase (2003), the idea for the implementation of magnetic field sensors inside catheters was theoretically justified, but without a real-life implementation because of the large size of the used sensors, as well as of the combination of 1D and 2D sensors. The signal processing electronics was a standard one and was not integrated in the sensor chip. The proposed solution here is a new and original one, integrating sensor and processing in the same chip. The construction is simplified with a reduced number of contacts, and it allows registration of the 3D sensor position with very high precision.
4.1 Micro-Device Structure

The device design of the new integrated 3D Hall sensor is shown in Figure 5. The sensor uses the first parallel-field Hall element, devised in 1983, which has three + contacts. Despite of its simplicity, this micro-transducer has characteristics and performance that are as good as those of all four-contact, five-contact, six-contact, and other parallel-field Hall modifications created until now (Roumenin, 1994, 2003; Roumenin & Nikolov, 2004). On the one side of the n-Si substrate, five n+ contacts are formed—one central C0 with square form and four strip contacts C1, C2, C3 and C4 placed at equal distances from the four sides of C0.

A deep p-well ring with a 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 device is separated into two equal parts diagonally through the same p-well ring, and the transducer region is open from the bottom side, which preserves the high value of the majority carriers mobility μ. The contacts C1-C0-C2 and C3-C0-C4, respectively, the energy supply E_n and the load resistors R1 - R2 and R3 - R4 define two functionally integrated triple parallel-field Hall elements with

![Diagram](image_url)

Fig. 5: 3D silicon-based magnetometer with simplified structure and enhanced sensitivity for miniaturization
common contact $C_0$, oriented one towards another at 90°. The sense contacts are the simultaneous supply ones.

4.2 Micro-Device Operation

The action of the 3D integrated Hall sensor is the following. At supply $E_n > 0$ and as a result of the symmetry of the transducer, there are four bias currents within the active region, which are two by two with opposite direction, i.e. $|I_{C0,C1}| = |I_{C0,C2}|$ and $|I_{C0,C3}| = |I_{C0,C4}|$. The sum of these components is equal to the current $I_{C0}$ via the central contact $C_0$. The mid-cross-section in $yz$ plane and the current lines of the triple $(C_1-C_0-C_2)$ Hall sensor are shown in figure 5. The picture for the other Hall element $C_2-C_0-C_4$ is the same. In presence of magnetic field $B_x$ the Lorentz deflection of the current carriers from $I_{C0,C1}$ and $-I_{C0,C2}$ at Hall angle $\Theta_H = \mu B_x$ leads to an increase of the one and to a decrease of the other potentials over $C_1$ and $C_2$, respectively. In this way a Hall voltage $V_{C1,2}(B_x) = V_x(B_x)$ between $C_1$ and $C_2$ is generated. The $B_y$ component generates Hall voltage $V_{C3,4}(B_y) = V_y(B_y)$ in the same way. Through direct measurement of the Hall voltages $V_x(B_x)$ and $V_y(B_y)$ at current $I_{C0} = \text{const.}$, we obtain the full information about the two components $B_x$ and $B_y$.

The operation principle being used and the high degree of symmetry of the device eliminate any $B_z$-field influence in the $x$- and $y$- channels. Of interest is the ‘sensing’ of the orthogonal to the device surface $B_z$- component. The Lorentz deflection of the currents $I_{C0,C1}$, $I_{C0,C2}$, $I_{C0,C3}$ and $I_{C0,C4}$ in $xy$ plane at Hall angle $\Theta_H = \mu B_z$ 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 $V_z(B_z)$ is developed on them. Thus, the full Hall voltage $V_z(B_z)$ between the pairs of contacts $C_1-C_3$, $C_1-C_4$, $C_2-C_3$ and $C_2-C_4$ is generated. The output signal $V_z(B_z)$ of the $B_z$- channel represents the differential voltage between two neighboring 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 the Hall voltage $V_z(B_z)$ measured between the contacts $C_1...C_4$ there is always cross-sensitivity voltage generated by the fields $B_x$ and $B_y$. As a result the voltage $V_z(B_z)$ can not be directly measured. In order to extract the net Hall voltage $V_z(B_z)$, it is necessary to express the signal $V_z(B_z)$ by a simple combination of voltages, generated by $B_x$, $B_y$ and $B_z$ 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 \( V_z(B) \).

The dynamic behavior of the new device is tested experimentally. The frequency response is measured as the dependence of the amplitude ratio of the respective channel output signal to the alternating current sine wave magnetic field (Figure 6). In the range \( 0 \leq f \leq 30 \text{ kHz} \) parasitic effects are not expected (3-D transducer with read-out circuitry). The high device symmetry and the technological lateral confinement overcome the channel cross-sensitivities and make it suitable for implementation in medical instrumentation.

5. CONCEPTUAL FUNCTIONALITIES OF ACTIVEVESSEL

Three-dimensional visualization. The fusion of IVUS with angiographies combined with the two-dimensional models of the vessel layers defined on the IVUS

![Graph](image)

**Fig. 6:** Measured power spectral density of the noise fluctuations for different supply current \( I_{C0} (1 \text{ mA}; 2 \text{ mA}; 3 \text{ mA}) \) at temperature \( T = 20^\circ\text{C} \)
images has permitted the visualization of these models with their tortuosity in 3D (Rotger et al. 2001). The way of placing the models along the 3D curve corresponding to the IVUS pullback is by orienting the X and Y axes of the IVUS image with the normal and binormal of the curve, respectively (Rotger et al. 2002). The three-dimensional visualization is performed in ‘near’ real-time and is a distinguishing feature of ActiveVessel.

Interactive Features. One of the crucial points in the image reconstruction algorithm is the initialization of the model in a noisy environment. In following the catheter path, the model may diverge from the true path. The physician can ‘drag’ the model (the curve) to approximate the true position of the catheter. The catheter path is corrected interactively to minimize the computation and error cost.

Further Development of ActiveVessel. Combining the three-dimensional placement of the IVUS data with tissue characterization will allow performing automatic diagnostics of the vessel pathologies. The next steps in the development of ActiveVessel will be interface oriented to make the dialogue with the cardiologist more flexible and with enhanced semantics. An approach for event-based multi-modal integration similar to Barakova & Lourens (2005) will be applied. ActiveVessel is compatible with Web-based technologies for remote access to medical and image databases.

6. CONCLUSIONS

This paper has presented ActiveVessel—a new multimedia medical workstation for the visualization, acquisition, and handling of different medical image modalities on- and off-line. Among its multiple functionalities are automatic catheter segmentation in angiography images, interactive model correction, and 3D visualization of vessel layers. ActiveVessel is under intensive development and will include the history of illness, analysis, and prediction based on perceptual and conceptual semantics. Our current research provides ActiveVessel with new technical solutions and in particular with the integration with a new magneto-sensitive micro-device inside the catheter for path reconstruction based on four (instead of three) sensor modalities. This makes ActiveVessel novel and useful in advanced cardiovascular practice.
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