3D Dynamic Model of the Coronary Tree

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Abstract

This article presents a new approach to build a kinetic elastic model of the coronary tree. Our purpose is to use this model in order to achieve spatio-temporal understanding of the cardiovascular dynamics.

A semantic network was developed to make a static structural model. Then, to estimate the motion, the network uses a Kalman filtering device guided by the trajectory model. The vessel deformation is detected in an energy-minimization procedure applying the active contour model (snake) technique.

A complete spatio-temporal description of the vessels (not just of sparse set of points) is obtained using a compact bi-dimensional B-spline representation where the movement of the vessel model is uniquely determined from the movement of the B-spline control points. In our two-dimensional B-spline dynamic model the directions determined by the iso-parametric curves correspond to the spatial and temporal vessel position, respectively.

1. Introduction

The main areas of research in computer applications to angiography imaging during the past 15 years were in geometric and densitometric methods to automate quantitative analysis of coronary arteriograms. The first steps were for assessment of coronary lesion severity in individual segments followed by a growing interest in automated identification and analysis of entire coronary tree.

Over the last few years, attention has directed to research towards 3D reconstruction from biplane projections [1], to better measurements on small vessels and to mix data coming from different imaging devices [2][3]. Despite of the increasing quality of the imaging equipment, the image quality, from a computer assisted analysis point of view is low. Congenital disease leads to special topologies (malformation) of the vessel tree. The noise level and artifacts remain high and a full automatic analysis tool has not been reported. Several computer assisted analysis methods have been proposed but all of them require the user intervention.

On the other hand, computer and communication technologies are growing at incredible speed, increasing performance with parallel decreasing in prices. Such phenomena opens new research fields with clear application feasibility that few years ago should have been only of theoretical scope.

Building a software coronary tree model has many interesting applications.

1. A way to make a tracking system for the coronary vessels dynamic.
2. Helper in the computer assisted analysis of coronary angiography sequences.
3. The model could be adapted to any particular image sequence coming from a patient and help the diagnosis by:
   - fast selection of the best frames
   - segmentation and measurements for quantitative stenosis assessment with less user intervention.
4. Integrated into imaging equipment, the model could help finding the best projection angles for a patient in real time.
5. Dynamic characteristics of the coronary tree can be assessed systematically for patients bringing more possibilities of clinical research.
6. Teaching and training.

This work deals with the building of a generic dynamic adaptive 3D model of the coronary tree.

The paper is organized as follows: section two describes the model architecture. Section three explains in short the building and use of the model and finally discussions and future plans are given.

2. Model architecture

There are three main components:

- A generic graph structure to support the semantic network.
- A Kalman filter device to estimate positions.
- A snake component to adapt the B-splines to the vessels shape.

2.1. Graph

Graph matching techniques [4] [5] have been successfully used in computer image analysis to label an extracted coronary tree after a segmentation process in angiographic images [6].

These techniques involve an anatomical representation of the coronary tree, a cost function and a segmented image to label. The labeling consist of minimizing the cost function matching the model against the image.

Basically there are to ways for representing the coronary anatomy through a graph:

1.- The nodes are related to the branching points and the arcs are related to the coronary segments

2.- The nodes are related to the arterial segments and the arcs are related to the relationships between the segments

The attributes generally used to characterize the coronary segments have been distances, branching level, orientation, mean lumen diameter, position, and length [6].

Applying an object-oriented paradigm and using the template mechanism for the graph implementation is generic and efficient in many ways: the structure is a template class where the data objects and the internal graph implementation details are template parameters. Nodes and arcs are classes, both inherit from a class named info, so the user of the graph can, by inheritance put any data in the graph. The user can decide where to keep the data objets (either in the nodes or in the arcs) at compile time.

Being an object oriented approach, each node and / or edge can store not only data but behavior associated to it (objects).

So the graph can hold both the anatomical and trajectories knowledge. The graph has been developed in ANSI C++ using the Standard Template Library as a base [7].

2.1.1 Data kept in the graph

A complete software model should consider not only anatomical but also dynamic features. A model like this could be a big step towards a computerized analysis system with high degree of automation.

The semantic network (graph), is able to hold both, anatomical and motion knowledge about a generic, average, coronary tree. The anatomical shape representation is achieved by interpolated cubic b-splines. The motion is represented as a sequence of 3D points keeping the average trajectory for each segment at any time.

In our graph we add to the attributes described in 2.1, a sequence of 3D positions for each segment. Moreover, the points are used as control points to build the cubic B-splines. While the data in 2.1 helps to the necessary image segmentation process, the B-splines keep information about the movement and shape.

The key idea is not to use point information but a curve to avoid many uncertainty problems otherwise present at later use of the model as a computer image analysis helper tool.

The sequences stored in the graph represent the 3D trajectory of the coronary tree.

At any time t, a set of 3D segment points modeling the tree can be obtained traversing the graph.

2.2. Kalman filter device

The discrete Kalman filter is a recursive predictive update technique used to determine the correct parameters of a process model. Given some initial estimates, it allows the parameters of a model to be predicted and adjusted with each new measurement, providing an estimate of error at each update. Its ability to incorporate the effects of noise (from both measurement and modeling), and its computational structure have made it very popular for use in computer vision tracking applications [8]. It has been suggested that, in the right situations, it performs better than any other linear filter [9].

A feature of the Kalman filter, not present in other statistical predictors, is its ability to adjust its own parameters according to the statistics of the measurements from each image. In other filtering methods, such as the alpha-beta filter, the percentage of the error (between the measured and the expected data used to adjust the model parameters) is kept as a constant for the entire image sequence, or is adjusted by the programmer. However, the Kalman filter allows this percentage to change automatically according to the current confidence in the accuracy of the state parameters.

The discrete Kalman filter is used in situations where a continuous process is sampled at discrete time intervals. In this research, the angiography image frames give the data at a constant time interval. These images are then sequentially analyzed using a Kalman filter to estimate the trajectory of the coronary tree within a determined error range. From the graph, the average trajectories are available as sets of B-spline control points, these are used as the process model in the filter. Then the filter can estimate new sets of control points for any 2D image sequence.

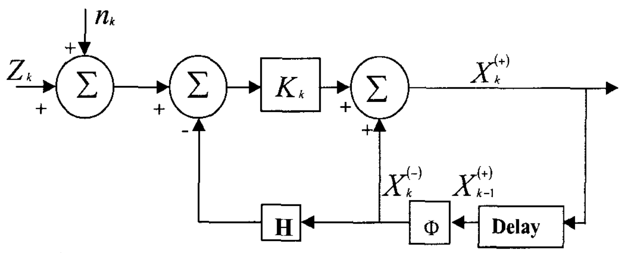

Figure 1. Kalman Filter Block Diagram

2.2.1. Description of the Kalman filter

The discrete Kalman Filter is an iterative procedure containing several elements. The filter is supplied with initial information, including the measurement error covariance, and estimates of the initial parameters and associated error, and these are used to calculate a gain matrix K. The error between the parameter estimates and the measured data Z is determined and multiplied by the gain matrix to update the parameter estimate and estimated error.

The updated error and parameters $X_{k-1}^{(+)}$ are used as input (see figure 1) to a model of behavior Φ (for us an average trajectory), to predict the projected error and parameters at the next temporal frame. A predetermined matrix H is applied to match the state vector to the measurement vector.

Initially, when the model parameters are only rough estimates, the gain matrix ensures that the data measurement is highly influential in estimating the state parameters. Then, as confidence in the accuracy of the parameters grows with each iteration, the gain matrix values decrease, causing the influence of the measurement data in updating the parameters and associated error to lessen. For the application of Kalman filters to the tracking of visual contours see [8]. For a detailed discussion about Kalman filters see [9].

2.3. Snake component

A snake is an energy – minimising curve, in our case spline, guided by external constraint forces and influenced by image forces that pull it toward features such as lines and edges. Snakes can be considered as active contour models because they lock nearby edges after a possible deformation based on image features and controlled by external forces based in a model of the image feature. The segmentation by snakes is defined as an energy minimisation problem. The snake deforms as close as possible to the image feature of interest (i.e. minimises its external energy), meanwhile keeps its shape as smooth as possible (i.e. minimises its internal energy).

Representing the position of the snake parametrically as $v(s)=(x(s),y(s))$, the energy functional of the snake can be written as:

$$E_{snake} = \int_0^1 E_{snake}(v(s))ds$$

$$= \int_0^1 E_{int}(v(s)) + E_{image}(v(s)) + E_{ext}(v(s))ds$$

where v is the spline, $E_{int}(v(s))$ is the internal energy, $E_{image}(v(s))$ is the image energy and $E_{ext}(v(s))$ the external constraints. The internal energy imposes a smoothness constraint. The image forces push the snake towards the feature (edge, line, etc.) and the external forces guide the snake to the desired local minima.

For a detailed description of snakes see [10] and [11]. For a description of splines see [12].

In our model, each set of B-spline control points, matching an artery at any time t is the input to the snake component in order to fit to the artery shape.

3. Building the model

Starting with anatomical 3D data [13] and the static model proposed by [6] a semantic network is defined and built including motion parameter attributes. Knowledge of the 3D structure and geometry of the tree is acquired manually from a sample of 30 angiography studies (with different projection parameters) of 50 frames to build the average model of the left coronary artery and circunflex in a first step. The average 3D anatomy and trajectories are reconstructed from the 2D images using the techniques explained in [14]. Each traversal of the network gives the 3D tree at a time t. The network shows adaptive properties both in anatomical structures and motion.

- Adaptive in shape through snakes.
- Adaptive in motion by estimation techniques.

The combination of motion estimation and segmentation by snakes makes possible to build a complete adaptive model.

3.1. Using the model

Tracking of the left coronary artery: from the 3D model, we obtain the 2D model matching the projection parameters of the sequence under analysis. Using the snakes and one image frame, we obtain the initial conditions for the Kalman filter. Then, the model acts as a control system using the average trajectories as the system model. The Kalman filter estimates the next frame position as a new set of control points. These control points are used then to make a new "measure" in the next image frame; using the snake component we let the B-spline adapt to the shape of the artery. The output of the snake (control points) is used as the new input Z to the Kalman filter (see figure 1).

4. Discussion

Many alternatives arise to the proposed architecture. Joining the Kalman filter and snakes as in [15] could be an improvement. After a careful validation the model could be used to research on the dynamic behaviour of the coronary tree. The model presented has been proposed and developed as a result of the project described in [16], so the effort to embed the model in a cardiac workstation shall be minim. Perhaps the more interesting step forward in our research is the use of B-splines surfaces. In our first approach (explained in this paper) the bi-dimensional space was implicit (traversing the graph). A more compact representation can be achieved considering a 2D spline. On such a surface, one iso-parametric dimension matches the time (trajectory) and the other matches the artery (shape). Currently there is a research effort to obtain, validate and compare the surface approach against the implicit one.

5. Future plans

Software development around the model is continuing on the PC-based Tele-cardiology platform, and once completed, the applications will be installed at the user sites for evaluation. The model is going to be installed into the cardiology workstation described in [16].

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