Interactive Catheter Shape Modeling in Interventional Radiology Simulation

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Abstract. Vascular catheterization provides a less invasive, non-surgical approach for treatment of vascular diseases. Although preformed catheters with diverse shapes and specific features are commonly available, clinicians still often use devices such as mandrels to modify the shape of catheters at the time of the clinical procedure. In this paper, we describe catheter shape modeling techniques. The purpose of catheter shape modeling is to provide clinicians with a means to modify catheter shape using a computer, and to practice catheterization procedures with this modified catheter on a computer based interventional radiology simulation system. We have proposed a 2-level design approach with the support of shapes and properties databases. In the first level, the shape of catheter is defined as a series of smoothly joined element segments. In the second level, we introduce catheter shaping algebraic operations recursively on the segments including merging, splitting, inserting and removing. We present our results by demonstrating the creation of right coronary artery catheters for different size and shape of aortic roots. The correctness of these catheters is validated with our catheter navigation simulator.

1. Introduction

Catheterization, the least invasive, non-surgical approach for treating vascular and other diseases, provides effective and quality patient care by significantly reducing patient discomfort, hospital stay and medical cost. It often requires the ability to enter the vascular system through needle puncture sites and to maneuver therapeutic or diagnostic devices through the vascular system, using x-ray imaging, to the target lesion in the body. With the smallest possible circular cross-sections, catheters are the most widely used devices in cardiovascular interventional procedures. The Catheters used in the interventional procedures are extremely diverse in shapes and specific features [1].

Specific catheter tip shaping is often required because of the wide variety of sizes and anatomical configurations of blood vessels and because the vascular characteristics of lesion vary significantly between different people. For example, in the field of interventional cardiology, there are at least three types of aortic configurations to be considered: normal, unfolded, and post-stenotic. The catheter

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shapes and dimensions have to be modified appropriately to accommodate different configurations. In the 1960s, before the availability of preformed angiographic catheters, Dr. Melvin P. Judkins shaped catheters at the time of each examination [2]. He placed a polyurethane tubing over a stiff wire bent to conform to the shape of the vessel, and then immersed the catheter in boiling water to soften it. When the assembly cooled, he withdrew the wire, and the catheter retained its shape. Although there are now many commercially available preformed catheters, clinicians still use devices like "Steam Shaping Mandrel" to modify the shape on the tip of the catheter.

In conjunction with development of our interventional radiology simulators[3-5], we developed a software system to design the shape of the catheter. The process is similar to the steam shaping and mandrel process, but instead of working with a physical device, the users create and test new catheter designs through software simulation. In such a system, the user can choose a catheter from the database with preformed shape and predefined material composition, and then modify its shape and size through a series of mouse clicks. In the next step, the clinician can use the interventional radiology simulator for pretreatment planning purpose[6] to determine the optimal shape of a catheter for a specific patient application and make the desired modifications in catheter shape using the method described in this paper.

We call our software system for shaping catheters "Digital Catheter Shaping Mandrel" or DCSM. Unlike our previous work [7], it is designed as a simple and user friendly system for training and planning through simulation. In this system, operations related to the manipulation of the piecewise curves are defined and implemented. Handy tools to carry out these operations are provided. Database of catheter shapes and materials are built. The output of the system is a finite element model (FEM) comprising a series of nodes in a format compatible with our simulator. Initial results of its application to interventional cardiology are described.

2. Methods

In DCSM, the catheter is defined as smoothly linked segments. For the convenience of manipulation, the catheter shape is represented by a tree structure as explained in the following subsection. In such a shape tree, a node corresponds to a subset of consequent segments and the leaf represents the element shape. The element shape is defined by parameters such as length, cross sectional radius, curve radius, *etc*. The modification of the catheter's shape is carried out through changing of the shape tree structure and/or changing of the element shape parameters. We have implemented handy tools to carry out these tasks. For example, the manipulation of the element shape such as elongation, bending and twisting are performed through mouse dragging. The manipulation on the element segment defined the first level of our 2-level design approach. In the second level, there are arithmetic operations including merging, splitting, inserting and removing segments that have been defined mathematically. Interactive tools to carry out these operations are provided.

Figure 1 illustrates the process of catheter shape modification. The user starts the process by selecting an existing catheter from databases of catheter shapes and materials. He/she then modifies the shape through adjusting the element shape parameters or a combination of arithmetic operations such as merging and splitting.

User friendly graphical display and intuitive interactions are provided to facilitate the execution of such operations.

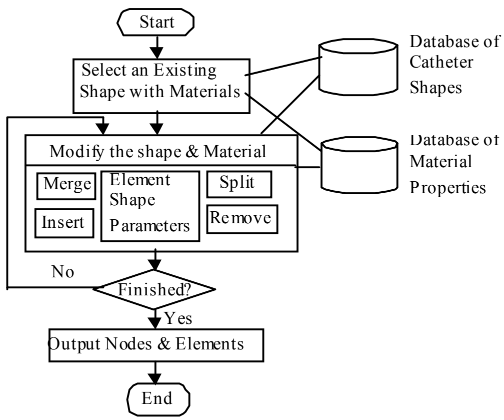

Figure 1. Flow chart of catheter shape modification

Material properties are critical to the behavior of the catheter. Physical parameters of the materials are stored in a database. These parameters are defined for each catheter element and are used in the finite element analysis of catheter navigation process. The purpose of finite element analysis is to determine the interactions between the catheter and guidewire, and between the catheter and the blood vessel wall with or without consideration of blood flow.

2.1 Catheter Shape Representation

A catheter is defined as a series of curved arc segments joined smoothly one after another. We use the operation " | " as the joining of two segments. For example, $S = S_1 \mid S_2$ means we join smoothly the head of S_2 to the tail of S_1. The shape of the catheter can be defined as $S = S_1 \mid S_2 \mid \cdots \mid S_N$, where N is the number of segments used to define the shape of the catheter. In addition, each segment in this expression can be formed by joining several component segments. Therefore the catheter shape could be represented as a tree shown in Figure 2. In such a tree, a node represents a shape segment. Siblings from left to right join subsequently to form the shape of their parent in the upper level. For example, $S_i^k = S_{i_1}^{k-1} \mid S_{i_2}^{k-1} \mid \cdots \mid S_{i_{ni}}^{k-1}$ means that the ith segment in level k consists of $i_{ni} - i_1 + 1$ segments in the level k-1. The sequence numbers of these segments are $i_1, i_2, \cdots, i_{ni}$, respectively. If a node in the middle level of the tree contains only one segment, the same segment is are defined as the descendant of this node at each lower level. In such structure, every level of the nodes could be joined together to represent the final shape. We represent such a

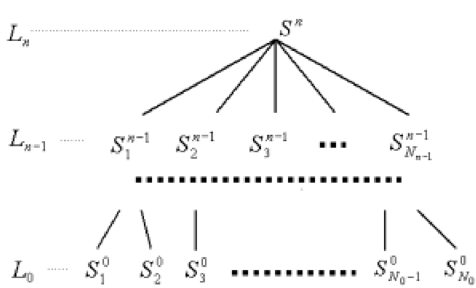

Figure 2. Tree representation of catheter shape

structure as $S = S_1^k \mid S_2^k \mid \cdots \mid S_{N_K}^k$, $k = 0,1,2,\cdots,n$, where N_k is the number of sub-shapes defined in the *k*th level.

2.2 Element Definition

An element shape is defined as a twisted arc. The shape of the twisted arc is defined in its own coordinate system. The origin of the coordinate system is defined as the point where the curve joins to other segment smoothly. At the beginning, the curve is straight and located along the positive *x*-axis. The shape of the element segment is defined by three parameters, the length (L), radius of arc (r) and radius of the cylinder around which the curve is twisted (r_c). The definitions of these parameters are shown in Figure 3.

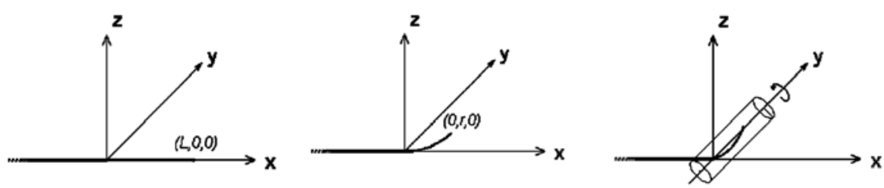

Figure 3. Definition of element shape

If L is the total length of the catheter curve element, each point on the curve can be assigned parameterized coordinates $C(s) = (x(s), y(s), z(s))$. The determination of these coordinates is carried out in three steps. In the first step, we determine the length of a straight line segment (L). In the second step, we bend it to an arc in the x - y plane. The radius of the arc r is determined by the user. The center of the arc is (0, r,0). By such definition, for $0 \le s \le L$, the parameterized coordinate of the arc can be expressed as,

$$(u(s), v(s), w(s)) = (r\sin(\frac{s}{r}), r(1-\cos(\frac{s}{r}),0) \tag{1}$$

In the third step, we twist the arc to make the curve wrap around a cylinder with radius r_c, the points on the curve can be expressed as:

$$(x(s), y(s), z(s)) = (r_c \sin(\frac{u(s)}{r_c}), v(s), r_c (1-\cos(\frac{u(s)}{r_c})) \tag{2}$$

2.3 Catheter Shaping Algebra

Typically, a catheter consists of several curves. For example, the left and right coronary catheters developed by Dr. Melvin P. Judkins[2] comprise primary, secondary and tertiary curves. In our model, each of these curves corresponds to an element segment or a segment formed by several elements. Catheter Shaping Algebra comprises of arithmetic operations that are developed to carry out operations such as merging, splitting, removing and inserting segments. For convenient of illustration, we use sub-shape to describe the segments that form a new catheter curve.

Merging

There are two sub-shapes S_i and S_j with lengths of L_i and L_j. Their shapes are defined in their own coordinate systems are $(x^i(s), y^i(s), z^i(s))$ and $(x^j(s), y^j(s), z^j(s))$ respectively. The merging operation $S = S_i \mid S_j$ will join the head the S_j to the tail of S_i smoothly. The length of the new curve is $L = L_i + L_j$. For sub-shape S_i, the coordinates of the curve remain unchanged, that is, for $s \le L_i$, $(x(s), y(s), z(s))) = ((x^i(s), y^i(s), z^i(s)))$.

The sub-shape S_j should be transformed to the new coordinate system through the following matrix. For $L_i < s \le L_i + L_j$,

$$\begin{Bmatrix} x(s) \\ y(s) \\ z(s) \\ 1 \end{Bmatrix} = \begin{bmatrix} r_{11} & r_{12} & r_{13} & U_i \\ r_{21} & r_{22} & r_{23} & V_i \\ r_{31} & r_{32} & r_{33} & W_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{Bmatrix} x^j(s) \\ y^j(s) \\ z^j(s) \\ 1 \end{Bmatrix} \tag{3}$$

The transform matrix must satisfies:

$$(U_i, V_i, W_i) = (x^i(L_i), y^i(L_i), z^i(L_i)) \tag{4}$$

$$\left(\frac{\partial x(s)}{\partial s}, \frac{\partial y(s)}{\partial s}, \frac{\partial z(s)}{\partial s} \right)_{s = L_i^-} = \left(\frac{\partial x(s)}{\partial s}, \frac{\partial y(s)}{\partial s}, \frac{\partial z(s)}{\partial s} \right)_{s = L_i^+} \tag{5}$$

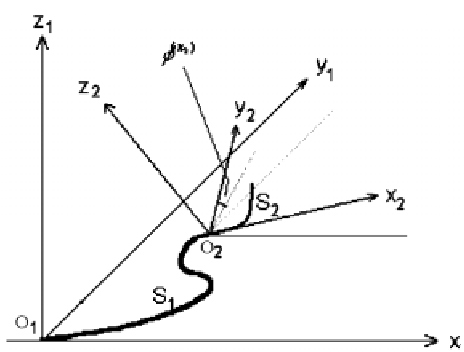

Figure 4. Merging of segments

It should be noted that Equation (5) determines only the vector of x-axis of local coordinate system of *i*th segment. The rotation angle $\phi_i^{(x)}$ is to be defined by the user to determine the direction of local y-axis. In Figure 4, origin of the segment S_2 is on the end point the segment S_1. The local x-axis of the segment S_2 is the tangential direction of S_1 at the tail. $\phi^{(x)}$ is defined as the angle between y_2 axis and its projection on the x_1 - y_1 plane. The vector for the direction of S_2 's local z-axis and the rotation matrix can be determined accordingly.

The merging of more than two segments is carried out from left to right, and the final curve is defined in the same coordinate system as that of segment 1.

Splitting

The splitting of a segment works with the sub-shapes that are formed through merging. Users can not split an element shape. For a curve shape $S = S_1^k \mid S_2^k \mid \cdots \mid S_i^k \mid \cdots \mid S_{N_K}^k$ and $S_i^k = S_{i_1}^{k-1} \mid S_{i_2}^{k-1} \mid \cdots \mid S_{i_{ni}}^{k-1}$, the splitting can be expressed as $S = S_1^k \mid S_2^k \mid \cdots \mid S_{i_1}^{k-1} \mid S_{i_2}^{k-1} \mid \cdots \mid S_{i_{ni}}^{k-1} \mid \cdots \mid S_{N_K}^k$. The resulted shape contains $N'_k = N_k + i_{ni} - i_1$ segments.

Removing Segment

Removing a segment can be applied to the element shape or a sub-shape in any level of the shape tree. For a curve shape $S = S_1^k \mid S_2^k \mid \cdots \mid S_i^k \mid \cdots \mid S_{N_K}^k$, the result of removing S_i^k can be expressed as $S = S_1^k \mid S_2^k \mid \cdots \mid S_{i-1}^k \mid S_{i+1}^k \mid \cdots \mid S_{N_k}^k$. In the tree structure shown in Figure 2, all children of S_i^k are removed accordingly. The catheter shape could be updated accordingly at any level of the shape tree.

Inserting Segment

Inserting a sub-shape can happen in any level of the shape tree. For a curve shape $S = S_1^k \mid S_2^k \mid \cdots \mid S_i^k \mid \cdots \mid S_{N_K}^k$, the results of inserting a shape $\overline{S}$ at position i could be expressed as $S = S_1^k \mid S_2^k \mid \cdots \mid \overline{S} \mid S_i^k \mid \cdots \mid S_{N_K}^k$. If an element shape is inserted in an upper level, we define it as its children until the lowest level of the shape tree currently under design. On the other hand, if the inserted shape is a sub-tree, its branches are inserted to the corresponding level of the current shape tree. If the depth of any sub-tree is less then the other, single child is added to the leaves to make the two sub-trees having the same level.

3. Results

The DCSM works on consumer PCs or workstations with a minimum of 64MB memory, preferably with an OpenGL graphics acceleration card. Figure 5 shows the graphics user interface of DCMS. We have provided a full set of user interactive functions to facilitate loading, modifying, saving and other related functions in the design of the catheter. The user can select a sub-shape at different level through a several mouse clicks. A sub-shape at any level could be removed or has its material property changed. Users can insert another shape in to the shape tree. If the involved shape is a sub-shape, it can be split at different level. However, if it is an element shape at the lowest level, its shape parameters can be adjusted freely. Editing functions includes changing of the following parameters: length, radius of arc, radius of twist cylinder. These functions include elongation/shortening, bending/straighten, and twisting/flatten. Rulers/grids can be displayed when users are modifying the shape of the element shape.

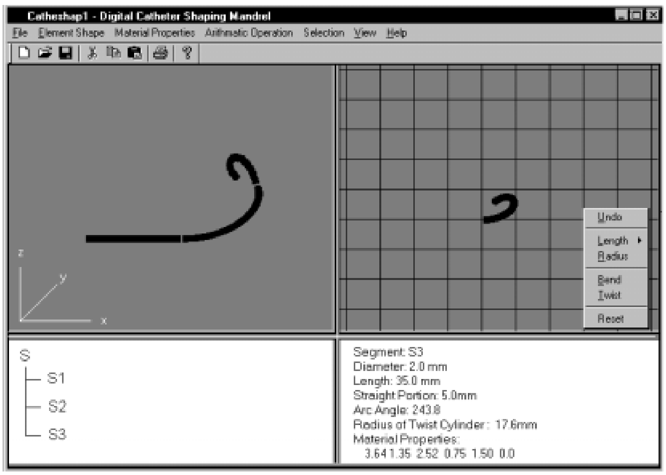

Figure 5. Graphical user interface for catheter shape design

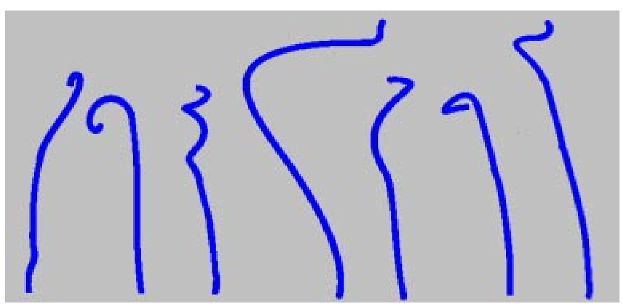

Figure 6. Examples of catheter shapes designed using DCSM

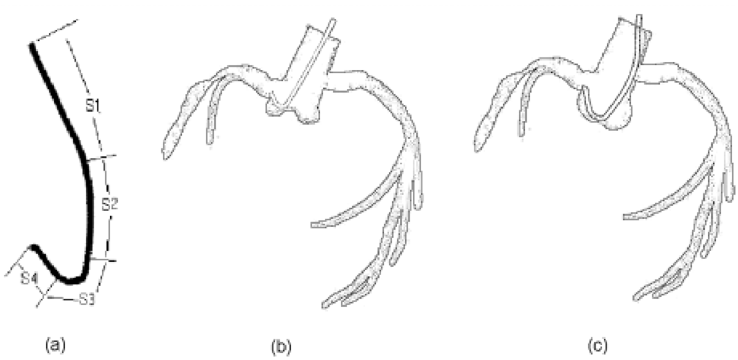

Figure 7. Right coronary catheter shape model and its navigation in heart model

Figure 6 shows some of the resultant catheter shapes we have modified from a straight catheter. Figure 7(a) illustrates the contributing components of our catheter shape model. Figure 7(b) and (c) show navigation of these right coronary catheters in a heart model having different size and shape of aortic roots.

4. Conclusion and Future Works

The DCMS is developed as a low-cost, user friendly and powerful tool for the clinicians to design and modify the catheter shapes in a computer simulation environment. It has been integrated into our interventional radiology simulation system for pretreatment planning. This software system has been validated by clinicians in the clinical context. This validation proves the usefulness and correctness of the underlying catheter shaping technique that has been defined mathematically in this paper.

The clinicians can use DCMS to modify catheter shape to allow for differences in human anatomical structures. However, an experienced clinician may demand more features, such as the manipulation of material properties. We also plan to add an expert system component to aid the catheter design and evaluation process. The goal of this system is to enable clinicians to design and evaluate catheter shape prior to its use in the procedures. But it is possible that the clinicians may be able to use this system to invent new catheters and/or a new procedure.

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