AN IMPROVED ENDOVASCULAR GUIDEWIRE POSITION SIMULATION ALGORITHM

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ABSTRACT

A novel and efficient method to simulate the behavior of guidewires in the vascular system is proposed in this paper. The graph-theoretical method is based on the principle of minimal total potential energy. We formulate the total potential energy in the vascular interventional system as the summation of the elastic energy of the guidewire and the energy due to the deformation of the vessel wall. A graph is constructed with low complexity ensuring the efficiency of the single source shortest path. Compared to previous results, experiments in three phantoms have been conducted to evaluate the performance of the proposed method and the results demonstrate that our method can achieve 20% improvement with faster running time.

Index Terms— Guidewire, graph, shortest path, simulation, bending energy, deformation

1. INTRODUCTION

Vascular Interventional Radiology (VIR) [1], also known as image-guided surgery, is a minimally invasive surgery (MIS) procedure, used to diagnose and treat a multitude of diseases across all body systems. In this technique, the physicians use X-rays, CT, ultrasound, and MRI to advance a catheter or probe in the body to treat the disease non-surgically. The recent decade has seen a wide use in vascular diseases, such as vascular stenosis, and aneurysms. The surgery is performed by two main kinds of cylindrical instruments, catheters and guidewires. A guidewire is a thin, usually flexible wire that can be inserted into a confined or tortuous space to act as a guide for subsequent insertion of a stiffer or bulkier instrument. The catheter and the interventional device(s) such as stents, balloons or coils, are brought to the site of intervention by moving them along the guidewire, i.e., the guidewire functions as a monorail for these devices.

This task is complicated because the surgeon relies primarily on 2D X-ray images. Further, the guidewire is steered remotely to the site of interest usually from femoral insertion site. Complications in such an approach are for example, vessel spasm or plaque release due to excessive force generated by the guidewire or interventional devices, especially occurring in older patients with weakened vessel structures. To optimize the interventional procedure (e.g., selecting the best fitting stent and catheter), it would be of value to compute the path of the guidewire in advance.

A number of methods have been proposed to simulate the behavior of guidewires in catheterization procedures. In [2], Xu *et al.* model the problem in a 2D pipe and present an efficient $(1+\varepsilon)$-approximation algorithm with theoretical guarantee. However, this algorithm cannot realistically simulate the complex behavior of guidewire in 3D. In 3D, many Finite Element Method (FEM) e.g. linear elastic [3] and static [4-5] finite element representations incorporates connected beam elements to model bending, twists and other deformations. In [6], a method was presented by expressing the positions of the guidewire as an energy minimization function and minimizing it in an iterative fashion, in which the guidewire was divided into connected beam elements and the proposed energy function model is based on Hooke's law [11] and theoretical mechanics on bending energy. To avoid the high computational cost of FEM, Schafer *et al.* make use of the beam-like approach of FEM techniques and [6], and reformulate the problem into an optimal path problem in [7]. This graph-based modeling takes advantage of the analytical modeling ideas and allows solution of the problem in a shorter time frame. However, the deformation of the blood vessels during the operation was not considered as part of the potential function in their method.

In this paper, we propose a novel method to simulate the position of guidewires and their interactions with blood vessels based on the principle of minimal total energy. The total energy includes the elastic energy derived from the bending of the guidewires and the potential energy due to the deformation of the vessel wall.

2. METHODS

In this section, we describe our approach to solve the guidewire problem. The guidewire path could lie anywhere inside the continuous free space of the vessel lumen. To determine the guidewire path, we first discretize the entire

vessel by sampling the points representing positions that the optimal path may pass through. A novel energy function is then used to approximate the energy of the path which goes through any three consecutive sampled points. Due to the quadratic nature of the energy function, the solution to any sub-path depends on the entire unknown optimal path and thus cannot be determined locally. Therefore, to solve the problem, we construct a graph G in which the energy information is represented by the edge's cost. And apply any single source shortest path algorithm such as Dijkstra's algorithm [10] on G to determine the optimal solution

2.1 Mesh Generation

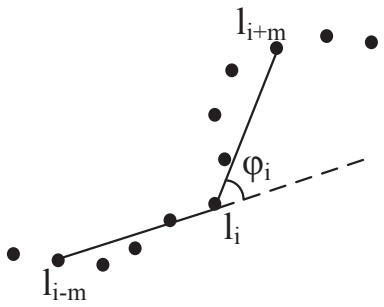


Fig.1. Central line points

We sample the points inside the vessel by constructing the mesh of points in the following way. The centerline of the vessel is represented by a set L of 3D points as shown in Figure 1. The i-th point of the centerline is denoted by $l_i \in L$ as the sorted order. We define the corresponding supporting plane u_i of l_i as the 2D plane perpendicular to $\overrightarrow{l_{i-1}l_{i+1}}$ and passing through l_i. The radius of the vessel at l_i is denoted by $r(l_i)$. On u_i, a circle c_i centered at l_i with radius larger than $r(l_i)$ is chosen to represent the intersection of the vessel and the supporting plane u_i. The reason we choose a larger circle is that the guidewire may cause the deformation of the vessel. To construct the mesh of l_i, N points equally distributed in distance in the plane are selected inside c_i in which each point is denoted by s_{ij}, where i is the index of the mesh and j is the index of the points on that mesh (see Figure 2).

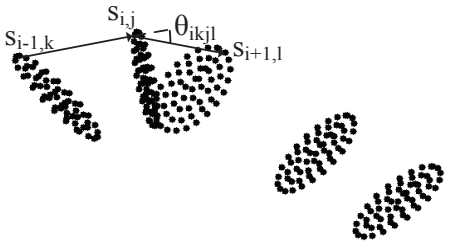


Fig. 2 Mesh

One way to sample the points is to construct the mesh corresponding to each centerline point and the total number of points is $|L|N$, where $|L|$ is the magnitude of L. On the other hand, we observed that the mesh points of adjacent centerline points are very close. Thus, we only construct the meshes for a subset of centerline points. More specifically, we divide L into groups with each group having 12 consecutive points. In each group, only one mesh is constructed of the central line point with the largest φ_i in which φ_i is the angle between $\overrightarrow{l_{i-m}l_i}$ and $\overrightarrow{l_i l_{i+m}}$, where m is less than 5. By doing this, compared to [7], we reduce the complexity of the vessel's representation and thereby improve the efficiency of our method.

2.2 Energy Function

Once the spatial representation of vessel is available, our goal is to find a path passing through exactly one sampled point of each mesh with minimum energy. To better approximate the energy of the real guide wire, two kinds of energies are considered in our model.

$$U = U_e + U_p \tag{1}$$

First, the elastic energy U_e is derived from the bending energy. Given a smooth parameterized planar curve s, its bending energy is defined as the integral of the squared curvature over the length of the curve, i.e., $E_b = \int_s \kappa^2 ds$ where κ is the curvature of the curve at point s. Let $s(t) = (x(t), y(t))$ be the parameterization of an arbitrary point on a smooth curve. Then the curvature [8] of the curve at $s(t)$ is given by $\kappa = \frac{|x'y'' - y'x''|}{(x'^2 + y'^2)^{3/2}}$. Intuitively, the curvature of a smooth curve at point P is defined as the inverse of its minimum curvature radius (i.e., the radius of the osculating circle at P (see Figure 3).

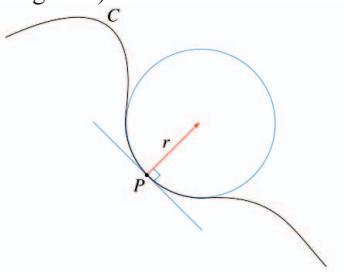


Fig. 3.Curvature

In our problem, we approximate the definition of the bending energy in [7]. For any three consecutive sampled points $s_{i,j}$, $s_{i-1,k}$, $s_{i+1,l}$ as shown in Figure 2, if the angle formed by $\overrightarrow{s_{i-1,k}s_{i,j}}$ and $\overrightarrow{s_{i,j}s_{i+1,l}}$ is represented

by $\theta_{ikjl} = \cos^{-1}(\overrightarrow{s_{i-1,k}s_{i,j}} \cdot \overrightarrow{s_{i,j}s_{i+1,l}})$, the elastic energy is defined as

$$U_e = \sum_i \theta_{ikjl}^2 \quad (2)$$

Secondly, the potential energy U_p is incorporated in our model due to the deformation of the blood vessel. By Hooker's law, the potential energy is proportional to the square of the deformation of the vessel. For the mesh generated by the l_i, U_p equals to zero if the distance between the sampled point s_{ij} and l_i is less than $r(l_i)$ since there is no deformation within the blood vessel. Otherwise, we define

$$U_p = \frac{1}{2}k(\overline{s_{ij}l_i} - r(l_i))^2 \quad (3)$$

where $\overline{s_{ij}l_i}$ is the distance between the s_{ij} and l_i.

2.3 Graph construction

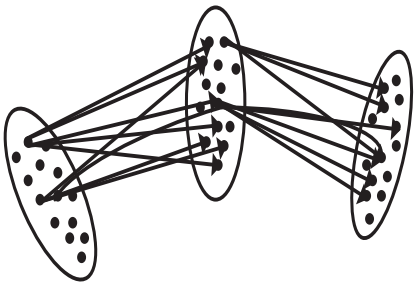


Fig. 4.Graph

We now describe the construction of the graph $G(V, E)$ to compute the optimal path with minimum energy U defined in last section. For any two sampled points $s_{i-1,k}$ and $s_{i,j}$ from adjacent meshes, a node $v_{i-1,k,i,j}$ is constructed. An edge with cost U is connected between two nodes if they (1) contain the sampled points from three meshes and (2) have one common sample point. For example, there is an edge between node $v_{i-1,k,i,j}$ and $v_{i,j,i+1,l}$ with the cost as the sum of U_p and U_e. In addition, two dummy nodes s and t are added to G in which s is connected to the nodes containing the sampled points of the first mesh and each node containing the sampled point of the last mesh is connected to t respectively with zero energy edges. The shortest path from s to t can be obtained by applying a shortest path algorithm such as Dijkstra's algorithm on G. Note we can also run the topological sorting algorithm on G since G is a directed acyclic graph with the running time linear to the size of G. Finally, we compute the smooth path by cubic spline interpolation on the sampled points obtained by the shortest path algorithm.

3. RESULTS

We conducted a set of experiments to compare the simulated guild wire and the real one in plastic phantoms. The encasing material of the phantom was Sylgard (Dow Corning, Midland, USA), a silicon based compound. The vessel wall was constructed from a polyethylene tube and the inner diameter is 3.65mm following the results published by Bharadvaj *et al.* [9] for the diameter of the internal carotid artery. The experiment was performed by inserting a real guide wire into a plastic tube and advancing it to a desired position. From CT scans of the phantom, we can obtain a 3D reconstruction of the guidewire inside the phantom. The experiment was repeated several times and the determined centerline was averaged to determine the guidewire's position inside of the phantom.

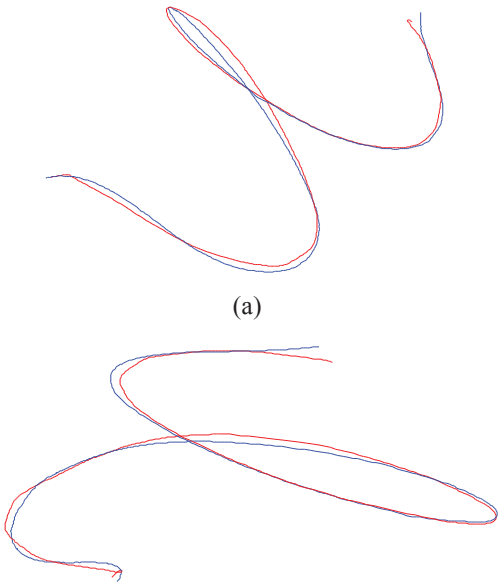
To evaluate our method, the simulation result G_s is compared to the real guide wire G_r. For each point i of G_r, the minimum distance between i and the closest point j of G_s is denoted by $d_{rs}(i)$.

$$d_{rs}(i) = \min(G_r(i) - G_s(j)) \quad (4)$$

Once the point correspondences between Gs and Gr are established, we use Root Mean Square (RMS) error to measure the difference between them.

$$RMS_{rs} = \sqrt{\frac{1}{r}\sum_i^r (d_{rs}(i))^2} \quad (5)$$

3.1 Performance comparison



(a)

(b)

Fig.5. Real (blue) and simulated (red) guidewire

Figure 5 shows the two views of real and simulated guidewire in phantom 1. Table 1 summarizes our simulation results of three different phantoms. In our simulation, if the central line is represented by M 3D points. We construct

M/11 meshes with each one contains N=60 sampled points. Compared to [7], we can achieve about 20% improvement of phantom 1 due to the consideration of the deformation energy. For phantom 2 and 3, we obtain comparable results since there is no deformation of the tubes.

Phantom number	Our result (mm)	Result by [7](mm)
1	1.1173	1.6172
2	1.3049	1.2917
3	0.9690	0.9624

Table 1

3.2 Mesh complexities

If we fix the number of meshes in the simulation, Figure 6 shows the relationship between N and RMS. As it is expected, the trend of accuracy of the simulation is improved with more points sampled in the mesh. However, it is not a strictly descending curve due to the errors caused by the discretization of the sampling. Thus for different applications, we can adjust N to achieve the optimal tradeoff between the performance and running time.

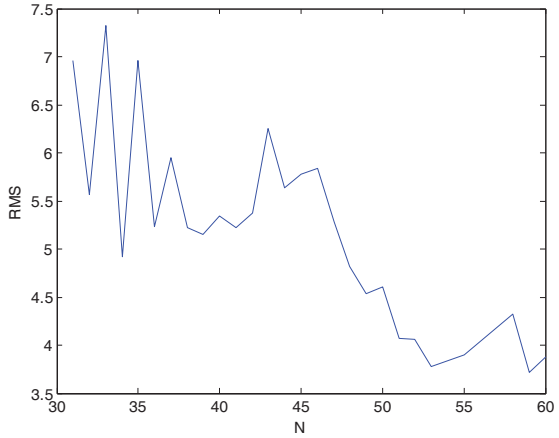


Fig. 6.RMS vs N

3.3 Radius of Mesh

In [7], the radius of the mesh is determined by the radius of the tube, as shown in the first column of Table 2. In our simulation of phantom 1, due to the deformation of the vessel, we construct the mesh with different radii. Table 2 (2nd to the last column) shows the results obtained using different radius with fixed N. All the results are better than those obtained with the fixed radius in [7].

Radius	1.728	2.016	2.304	2.592	2.880
RMS	1.6172	1.1551	1.1173	1.2994	1.4112

Table 2

4. Conclusion and discussion

In this paper, we proposed a novel simulation approach incorporating the bending energy of the guidewire plus the deformation cost of the blood vessels. Compared to [7], the approach achieves better results when the phantom undergoes small deformations. The reduced complexity of the graph construction results in shorter running times. The proposed technique yields reproducible and accurate guidewire positions within a short, clinically relevant time frame, which may be useful in facilitating neurovascular interventions.

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