Safety Protection Based on Electromagnetic Navigation in Robot-assisted Vascular Interventional Surgery

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Abstract—**Applications of robotic technology in vascular interventions have potential advantages over conventional vascular surgery. Despite its high-precision and dexterous manipulation, absence of intuitively haptic feedback has been proved to increase the risk of other complications. In this paper, we propose a safety protection framework to prevent the blood vessel from penetration by guide wire in robot-assisted vascular interventional surgery. A 3D vascular model serving as the virtual environment is constructed from the CT images. Then, the centerline of the interventional vascular is extracted and the inner region of the blood vessel is graded. During the surgery, an electromagnetic system is employed to track the guide wire in real time, based on six 5DOF magnetic sensors mounted at the leading end. After a registration mapping the patient's coordinate to image coordinate, the motion of guide wire can be tracked and its trend is simulated with a collision between guide wire and vascular wall detected in real time. To evaluate the proposed method, an experiment in a 3D printed vascular phantom is performed, where the experimental results revealed that the safety protection could be significantly improved during the procedure of inserting guide wire along the vascular to the treatment site.**

Keywords; Safety protection; robotic surgery; electromagnetic navigation; vascuar intervention; guide wire simulation;

I. INTRODUCTION

Cardiovascular disease (CVD) has been a major cause of mortality over the past few years worldwide, which accounting for 45% of all deaths[1]. Treatments including medical management and open surgical techniques were taken historically. With the interventional radiology and the transcatheter technology embraced by many surgical disciplines, endovascular surgery as the most common minimally invasive surgery provides patients who unfit for the open surgery to undergo treatment an alternative for its smaller incisions, lower mortality rate and less recovery time.

However, numbers of randomized trials conducted by Smith[2] and Ghanem[3] showed that there existed a higher risk of embolization and other vascular complications over open heart surgery involved by the catheter or guide wire during its manipulation in the vascular intervention. More specifically, absence of vivo 3D intra-image and limited range of motion result in massive wall-hit in the endovascular surgery procedure. Surgeons always have no specific decisions about the contact between instruments and tissues. Furthermore, exposing physicians to the ionizing radiation for long term might cause irreversible renal damage. In view of these plagues, the robotic endovascular technology as an alternative has been introduced by surgical disciplines over the past years. Thierry[4] and Justin[5] had described the methods to replace an aortic valve using robotic endovascular techniques in their studies, which gained positive outcomes. Radoslaw[6] also explained the feasibility of robotic endovascular technology, which potentially reduces the contact between the vascular wall and the embolic risk during endovascular manipulation. Within robotic endovascular surgery, preventing vascular and tissues from damage due to excessive force of insertion should be of great concern. Improvements in hardware about catheter and guide wire have been researched by E.Marcelli[7] and Hedyeh [8], on which a force sensor mounted at the tip of catheter to measure the resistance encountered by the guide wire while advancing. A novel catheter prototype which can measure the tip side force and friction between catheter and blood vessels had been designed by Polygerinos[9]. A robotic catheter manipulation system with force feedback presented by Xu[10] can facilitate the manipulation of inserting catheter into vascular.

Though these improvement had reduced the damage and numbers of wire-tissue contacts, the expense of these dedicated catheters and devices has increased much. There has another solution via analyzing the motion of guide wire while advancing which has rarely been researched.

Based on the simulation of guide wire, we proposed a novel framework to prevent vascular from damage. With the assistance of the Electromagnetic Tracking (EMT) system, the guide wire can be tracked and its motion can be simulated based on Kirchhoff elastic rod[11]. Accordingly, the position of guide wire at next time stamp can be estimated. In addition, a collision between vascular wall and guide wire as well as its response on vascular wall are calculated.

The outline of our study is shown as Fig.1.SectionII describes the details of the framework. Section III presents the experiments on a 3D printed vascular phantom. And then followed by the conclusion in Section IV.

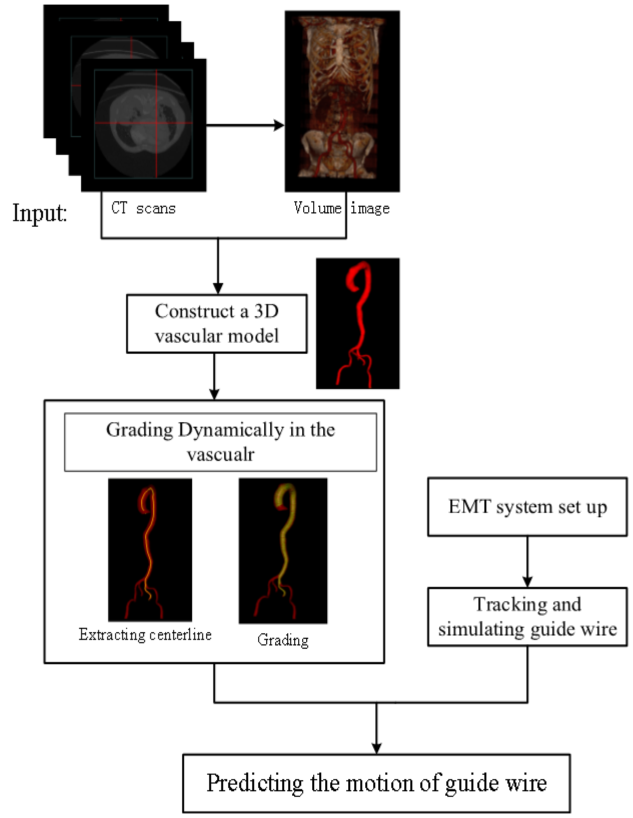


Figure.1 The proposed safety protection framework in robot-assisted vascular interventional surgery.

II. METHOD

A. *Construct a 3D Vascular Model*

In order to introduce the guide wire and catheter to the treatment site (for brevity, we use “guide wire” to represent “catheter” or “guide wire” hereafter), firstly, we construct a 3D vascular model serving as the virtual environment. The model construction consists of two key parts: vascular segmentation and vascular modeling. A semi-automatic algorithm inspired by the work proposed in [12] is employed to segment the vascular from CT image with parameters of slice thickness 1.0mm, image solution 512*512 and spacing 0.683mm*0.683mm*0.7mm. Then a surface model of the segmented vascular, which is composed of massive triangular facets, is constructed on the basis of marching cube algorithm [10]. Meanwhile, every facet in our model is applied by an elastic module as we suppose that the vascular is of uniform elasticity. The segmentation result and vascular model are shown in Fig.2

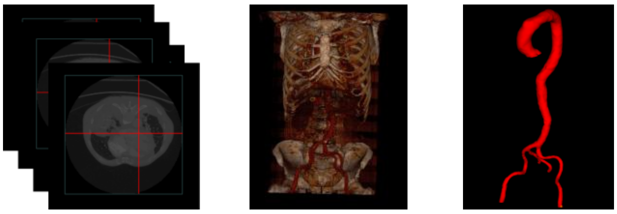

(a) (b) (c)

Figure.2 Construct 3D Vascular Model. (a)The preoperative CT scans. (b) The 3D image by volume rendering. (c) The constructed vascular model

B. *Grading Dynamically in the Vascular*

In vascular intervention, the inner of blood vessel is dynamically graded into three areas: safe area, warning area and dangerous area, which can provide physicians intuitively guidance to introduce the guide wire to treatment site. Inspired by the work in [10], a fast centerline extraction algorithm is employed to compute the centerline of blood vessel. Based on the centerline, a curvature weighted method has been proposed to divide the vessel. The grade area can be formulated as:

$$\begin{aligned} &Safe: 0 \le d < \frac{1}{3}(w_s \times c_p + 1) \times r_p \\ &Warning: \frac{1}{3}(w_s \times c_p + 1) \times r_p \le d < \frac{1}{3}(w_d \times c_p + 2) \times r_p \\ &Dangerous: \frac{1}{3}(w_d \times c_p + 2) \times r_p \le d < r_p \end{aligned} \tag{4}$$

Where w_s , w_d are the predetermined weights. r_p , c_p represent the radius and curvature at point p of the centerline, respectively. And d demotes the distance of guide wire to vascular wall.

C. *Tracking and Simulating Guide Wire*

In our robot-assisted endovascular intervention system, a guide wire on which six 5DOF sensors are mounted at the leading end is employed. Sensors could be tracked accurately to 0.6mm by an EMT System. The position of these six 5DOF sensors are used to fit a cardinal spline to construct a model of the front part of the guide wire in the virtual reality environment. Different from other interpolation spline, every slope of its nodes could be given by previous and next positions. And the boundary condition of each curve can be formulated as:

$$\begin{aligned} &P(0) = p_k \\ &P(1) = p_{k+1} \\ &P'(0) = \frac{1}{2}(1-t)(p_{k+1} - p_{k-1}) \\ &P'(1) = \frac{1}{2}(1-t)(p_{k+2} - p_k) \end{aligned} \tag{1}$$

Where t denotes a tensor parameter controlling the degree of tightness, k represents the k th node.

To simulate a physically-based guide wire, the elastic energy are formulated based on the Kirchhoff elastic rod. And the elastic energy in our guide wire composes of stretch energy $E_{stretch}$ and bending energy E_{bend} .

$$\begin{aligned} E &= E_{bend} + E_{stretch} \\ E_{bend} &= \frac{1}{2}\int_{L} K_b (\mathbf{w}-\bar{\mathbf{w}})^T (\mathbf{w}-\bar{\mathbf{w}}) ds \\ E_{stretch} &= \frac{1}{2}\int_{L} K_s (|\gamma'(s)|-1)^2 ds \end{aligned} \tag{2}$$

Where $\mathbf{w} = (w_1, w_2)^T$, w_1, w_2 represent the curvature vectors. And $K_b = E(\pi r^2/4)$, $K_s = E_s \pi r^2$ [13] with E representing the flexural modulus, E_s representing the stretching Young's modulus. $|\gamma'(s)|$ denotes the stretch radio of guide wire.

The equation above should be discretized for numeric solution:

$$\begin{aligned} E_{bend} &= \frac{1}{2}\sum_{i=1}^{n} K_b \left(\frac{\kappa b_i}{\bar{l}_i/2}\right)^2 \frac{\bar{l}_i}{2} = \sum_{i=1}^{n} \frac{K_b(\kappa b_i)^2}{\bar{l}_i} \\ E_{stretch} &= \frac{1}{2}\sum_{i=0}^{n} K_s \left(\left|\frac{e^i}{\bar{e}^i}\right|-1\right)^2 \end{aligned} \tag{3}$$

Where i represents discrete segment index of guide wire, $e^i = x_{i+1} - x_i$, $\bar{l}_i = |\bar{e}^{i-1}| + |\bar{e}^i|$, x_i is the coordinate position of i th node.

D. *Predicting the Motion of Guide Wire*

Since the safety protection behavior of guide wire will differ when a collision to the vascular wall occurs, a real-time collision detection must be performed to prevent the guide wire from penetrating through vascular wall, such that different prediction strategies can be adopted. Predicting behavior of guide wire consists of three key parts: collision detection, computation of guide wire's position at next time stamp and collision response. An efficient collision detection algorithm using bounding volume hierarchies of k-DOPs inspired by [14], which can logarithmically reduce the time-consuming, is employed.

Then, based on the location and velocity of each mass point can be obtained by EMT System, the energy equation in section B can be presented. Furthermore, the force on each node is formulated by the Lagrange equation of motion: $M\ddot{\mathbf{x}} = -(dE/d\mathbf{x})$. Finally, the dynamic iteration[15] of the computation of guide wire's position is presented in Eq. (5):

$$\begin{aligned} \begin{bmatrix} \Delta\mathbf{x} \\ \Delta\mathbf{y} \end{bmatrix} &= \Delta t \begin{bmatrix} \mathbf{v}_t + \Delta\mathbf{v} \\ M^{-1}\mathbf{f}(\mathbf{x}_t + \Delta\mathbf{x}, \mathbf{v}_t + \Delta\mathbf{v}) \end{bmatrix} \\ \mathbf{f}(\mathbf{x}_t + \Delta\mathbf{x}, \mathbf{v}_t + \Delta\mathbf{v}) &= \mathbf{f}_t + \frac{\partial\mathbf{f}}{\partial\mathbf{x}}\Delta\mathbf{x} + \frac{\partial\mathbf{f}}{\partial\mathbf{v}}\Delta\mathbf{v} \end{aligned} \tag{5}$$

Where $\Delta\mathbf{x}$, $\Delta\mathbf{v}$ are the variation of location and velocity in time step Δt . $\mathbf{v}_t$ and $\mathbf{x}_t$ are the velocity and position at time t. $\partial\mathbf{f}/\partial\mathbf{x}$, $\partial\mathbf{f}/\partial\mathbf{v}$ are Jacobian matrices of the force with respect to positions and velocity, M is a mass matrix associated to mass point positions.

The penalty method and constraint method are two classes of schemes to handle collisions among the deformable objects. Since constraint methods tend to be expensive or sensitive to numerical problems and require moreover effort implementation[15], the penalty method is employed based on the collision detection and evaluation of guide wire's location.

E. *Registration*

A fiducial landmark registration[12] which can minimized the mean-squared distance between the actual and virtual coordinate should be performed. After that, a transformation $TM_{world->image}$ is applied to each point tracked by an EMT system.

III. EXPERIMENTS AND RESULTS

The proposed method in our safety protection framework was validated via a phantom study. Fig.3 shows the hardware setup of the experiment.

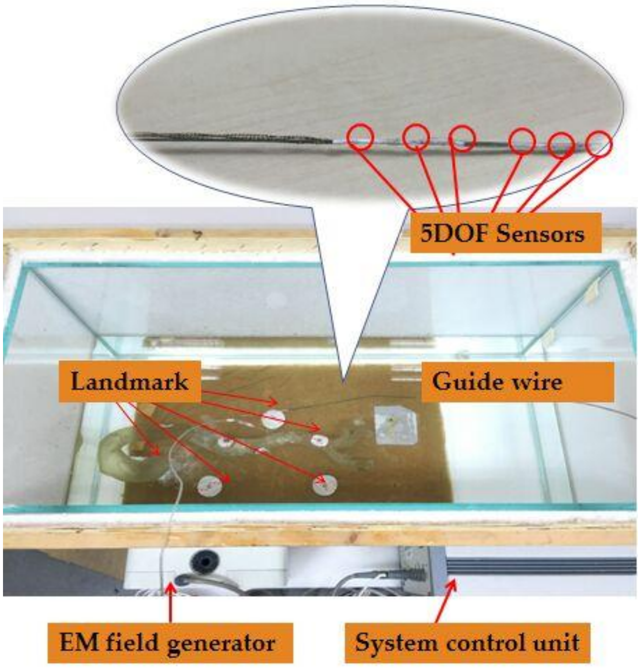


Figure.3 Experiment hardware setup

A. *Experiment Setup*

The vascular phantom was made of silica gel and veroclear hybrid materials by an Object500 Connex3 3D-printing machine from Stratasys Company, with its elasticity modules of 1.2GPa. A clinical guide wire from Cordis Corporation with type of EMERALD Guide wire 0.035 is utilized to be inserted into phantom. As described in section II, the magnetic sensors were mounted on the leading end in our experiment. Meanwhile, the EMT System (NDI Aurora) was utilized to track the position of guide wire in the experiment. And the computing device was a PC with 32-bit windows, Intel(R) Core i5 CPU and 5 GB RAM.

B. *Phantom Experiment*

In the experiment, firstly, a phantom was placed in the standard magnetic field generated by the EMT system. Then, the structure of vascular was segmented from the phantom's CT scans (Fig.4 (a)) and a 3D vascular model (Fig.4 (b)) was constructed. Based on the vascular model, we extracted the centerline by manually selecting an entry point and exit point on the 3D model. Meanwhile, three different areas inner of the vessel were graded as shown in Fig.4(c). Afterwards, a spatial registration was performed to map the real-world coordinate to image coordinate. And the Fiducial registration error (FRE) and Target registration error (TRE) [16]were computed in each case shown in TABLE 1.

When the guide wire was inserted into the vascular, its motion would be tracked via the EMT system and simulated physically in real time. Finally, combining efficient collision detection among guide wire and vascular with motion estimation of guide wire, our safety protection approach will responds different safety levels as shown in Fig.5, where (a) ,(b) and (c) represent the safe, warning and dangerous state of guide wire, respectively.

To better validate the method of collision response, we performed a group of experiments that guide wire was inserted into phantom at different velocity and included angle to collide with vascular wall. The virtual feedback force had a positive correlation with velocity and included angle when collision occurs as shown in Fig.6.

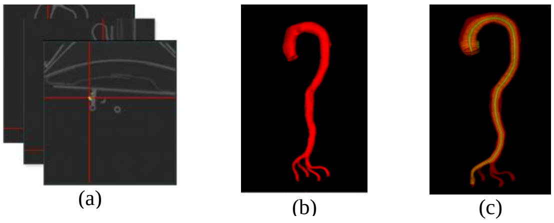
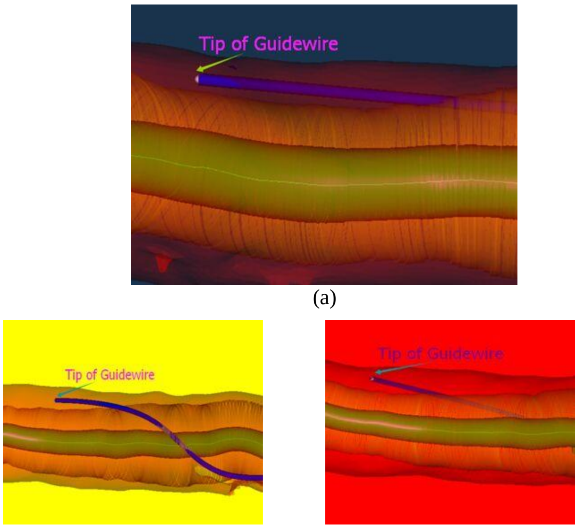

(a) (b) (c)

Figure.4 Construct 3D Vascular Model of Phantom. (a)The preoperative CT scans. (b) The constructed vascular model. (c) Graded areas inner of the vascular

TABLE 1. The registration error in a phantom study

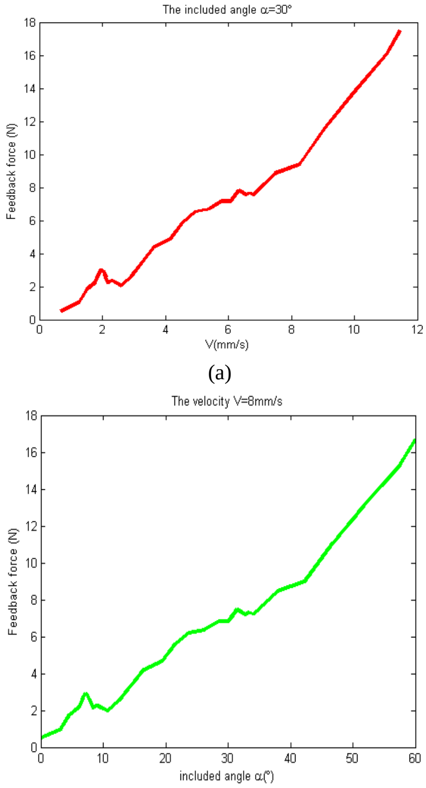
Group	FRE	TRE
1	1.3mm	2.1mm
2	1.7mm	2.8mm
3	1.3mm	3.2mm
4	1.0mm	1.9mm



(a)

(b) (c)

Figure.5 Different state of guide wire at next time step. (a) Safe state. (b) Warning state. (c) Dangerous state.



(a)

(b)

Figure.6 Feedback force when collision occurs. (a)Feedback force at different velocity. (b)Feedback force at different included angle.

IV. DISCUSION AND CONCLUSION

A safety protection platform based on electromagnetic navigation has been proposed to prevent blood vessel from damage in robotic vascular interventions. It can be utilized to facilitate surgeons to introduce the guide wire to treatment site by avoiding the penetration of vascular wall while guide wire advancing. Under the tracking of EMT system, the position and orientation of guide wire are obtained as well as its motion is physically simulated based on Kirchhoff elastic rod. Accordingly, the protecting procedure is achieved via combining the virtual and reality environment. The experimental results demonstrated that the safety protection can be significantly improved during the procedure of inserting guide wire along the vascular to treatment site as shown in Fig.5. Meanwhile, correlation of the computed virtual feedback force to velocity and included angle also proved to be positive as shown in Fig.6. As for the existing method[7][9], a great deal of improvement in hardware such as developing dedicated guide wire or catheter has been made. Compare to these improvement in hardware, our method can be more economic and flexible, and have great potential for safety control when applying robotic vascular intervention.

This framework remains further improvements. Currently, the influence of the blood flow to simulation of guide wire has not been taken into consideration, though it can obviously improve the accuracy of our safety protection platform. Besides the phantom study, our framework will be validated under the clinical manipulation. As a pilot study, the experimental results mostly are assessed visually. A quantitative evaluation need to be performed.

ACKNOWLEDGMENT

This research is partially supported by the National Key research and development program (2016YFC0106200) and 863 national research fund (2015AA043203) as well as the Chinese NSFC research fund (61190120, 61190124 and 61271318).

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