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Simulation Analysis of Catheter Bending in Vascular Intervention Robot Based on ANSYS

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***Abstract* - Vascular interventional surgery has played an important role in the treatment of cardiovascular and cerebrovascular diseases. The corresponding vascular interventional robots are also developed. In our previous work, the interventional operation robot was developed to operate catheter or guidewire. However, in the process of conveying the catheter, the surgical accuracy will be affected by the inevitable bending deformation of the catheter in the sleeve. In this paper, in order to improve the accuracy of position control, we simulated the deformation of the catheter and obtains the displacement error caused by the catheter based on the ANSYS software. The results proved that the deformation of the catheter affects the precision of position control, and simulation results are prepared for the later compensation algorithm.**

***Index Terms* – Catheter bending; Vascular intervention robot; Simulation; Compensation**

I. INTRODUCTION

The interventional surgery is a type of minimally invasive operation which can reduce hospitalization time and greatly decrease patient morbidity compared to traditional methods. In recent years, minimally invasive vascular surgery is widely applied in treatment of cardiovascular diseases, and robotics has expanded significantly in the field of minimally invasive cardiology. There are increasing remote-controlled Vascular Intervention Robot (RVIR) have been proposed in previous researches [1], [2].

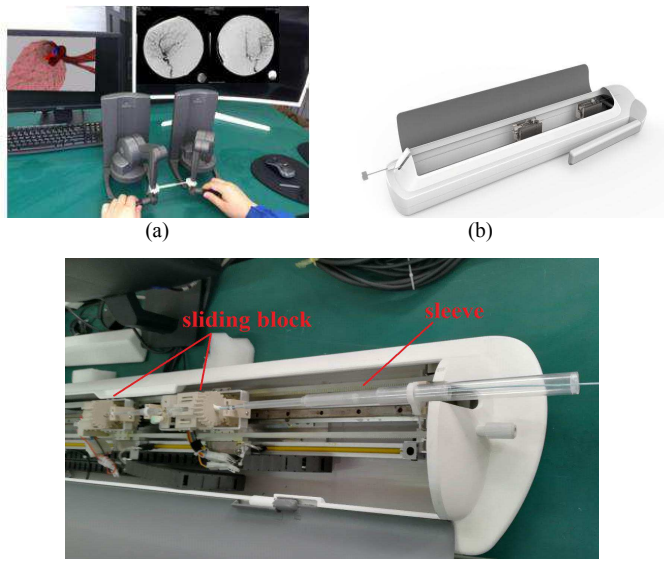
Up to now, four main commercial RVIRs have been developed. The Corpath robot system, developed by Corindus Vascular Robotics [3], can manipulate catheters for vascular applications by using friction wheels to grip and rotate the catheter. The Sensei and Magellan robot systems, designed by Hansen Medical [4]-[6], use steerable catheters and sheaths to conduct remote operations, and have been successfully used in different clinical applications. Catheter Robotics Inc. designed the Amigo robot system [7], which achieves three degrees of freedom (DOF) manipulation of the steerable catheter on the slave side and provides a remote controller with push buttons on the master side. The Niobe robot system, developed by Stereotaxis Inc. [8], uses controlled magnetic fields to operate a catheter connected with a magnet. A number of studies on RVIRs have been published [9], [10].

There are still many problems with the remote-controlled vascular interventional robots. Firstly, catheters and guidewires are simultaneously operated to complete a surgery, especially in some complex surgeries. It is only when the support of the catheter and the guidance of the guidewire are used simultaneously that the surgeon can operate the catheter/guidewire to complete a complex surgery. Secondly, catheters and guidewires must be accurately manipulated by remote-controlled vascular interventional robots (RVIRs) without causing damage to their own surfaces. Incorrect replicated motion of the catheter or guidewire on the slave side will cause medical accidents. Catheters or guidewires with damaged surfaces may result in thrombus in the blood vessels.

In our previous research, several novel active catheter systems were developed. To address these challenges, we proposed a novel solution and fabricated a novel remote-controlled vascular interventional robot (called RVIR-CI) [11]-[15] and then fabricated the second generation robot [16], [17] (called RobEnt) (Fig.1) by improving the RVIR-CI.

In the RobEnt of our research, there is a catheter guide sleeve for preventing the catheter from buckling in the slave end. However, this improvement has led to new problems. When we use the catheter manipulator to pull/push the catheter, the catheter will buckle slightly even though a catheter guiding sleeve is used to prevent the catheter from buckling. The deformation of the catheter will have an adverse effect on operation accuracy. In order to compensate the motion error caused by deformation, the kinematics of catheter deformation need to be analysed and the catheter motion control algorithm needs to be redesigned. This paper is to do research on the deformation of the catheter in the sleeve by simulation and obtain the displacement error.

In this paper, the simulation of the catheter deformation in the sleeve is analyzed. In section II, our intervention surgical robots is introduced and its problem needing to be improved is explained. In section III，the method of simulation of catheter is presented and the physical model of the catheter is built using the elastic rod model through the analysis of the deformation of the catheter in the sleeve. In section IV, the



(a) (b) (c)

Fig. 1. Remote-controlled vascular intervention robot: (a) master controller; (b) slave manipulator; (c) sleeve and sliding block in the slave manipulator.

buckling of the catheter in the sleeve is simulated using the method mentioned in section III in the ANSYS environment. In section V, simulation results are analysed and discussed. In section VI, the research work is concluded and the future work is indicated.

II. Robot system

When the RVIRs are used to perform surgery, the surgeon operates the master controller on the master side, while the slave manipulator replicates the operations of the surgeon on the slave side. The surgical robot's structure is as Fig.1 shows. The RVIRs incorporate two components, respectively, the master controller in the master side and the slave manipulator in the slave side.

When the slave manipulator replicates the operations of the surgeon on the slave side, the catheter buckles and appears deformation phenomenon as the sliding block moves back and forth (Fig. 2). Thus, we design a catheter guiding sleeve (Fig. 1(c), Fig. 3) in the slave end to solve the bending problem. However, there emerges a new problem that the catheter will slightly buckle under the constraint of the sleeve. The catheter deformation results in the displacement error during the catheter movement, causing the precision decrease of the position control.

In order to prevent the surgical risk and improve the position control accuracy, the catheter dynamics is analyzed and simulated in the following paper.

III. Methods of simulation

In this section, the nonlinear finite element analysis method of the catheter simulation will be introduced. The nonlinear behavior of the catheter in the case of boundary constraint

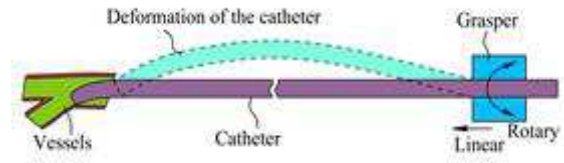


Fig. 2. Catheter buckling when operating it.

Fig. 3. Catheter guiding sleeve.

conditions will be studied.

A. Nonlinear finite element analysis

The Finite Element Analysis (FEA) uses mathematical approximation to simulate the real physical system (geometry and load conditions). The simple and interacting elements, that is the units, can be used to approximate the real system of infinite unknowns with a finite number of unknowns [18]. The material of the catheter is nonlinear, and the deformation is diverse and complex, so it is impossible to obtain the exact simulation solution of the deformation problem. The finite element method is initially called the matrix approximation method, which can get the approximate solution close to the real problem. It not only has high precision, but also can adapt to various complex shapes, so the finite element method is used to obtain approximate solutions.

For material nonlinearity, the fundamental equation of finite element is

$$[K]\{\mathrm{u}\}=\{\mathrm{R}\} \tag{1}$$

where $\{\mathrm{u}\}$ is the node displacement array, $\{\mathrm{R}\}$ is the external load array, $[K]$ is the total stiffness matrix, $[K]=\sum_{1}^{e_0}[K]_e$, e_0 is the total number of units, $[K]_e$ is the element stiffness matrix, can be expressed as

$$[K]=\int_{V_e}[B]^T[D][B]dV_e \tag{2}$$

where V_e is the unit volume, $[B]$ is the geometric matrix, also called the strain matrix, $[D]$ is a constitutive matrix. For linear deformation of nonlinear materials, $[B]$ is still a constant matrix, but $[D]$ is no longer a constant matrix, it is a function of node displacement, $[D]=[D(\{u\})]$, that is, put it in the equation and get

$$[K(\{u\})]\{u\}=\{R\}. \tag{3}$$

The total stiffness matrix $[K]$ in the upper equation is a function of the node displacement, and the displacement

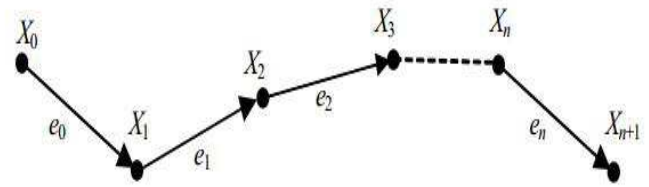


Fig. 4. Catheter discretized into N spatial control points.

$\{u\}$ of the node can be obtained by solving the nonlinear equation (3).

No matter what kind of the nonlinear finite element problems ultimately is to solve a set of nonlinear equilibrium equations. The basic idea of solving nonlinear equations is to transform nonlinear problem into a series of linear questions [19]. There are three common methods: Firstly, the iterative approach. The essence of the iterative method is to approximate the nonlinear solution of equilibrium with the unbalanced linear solution under the action of total load, and the iterative process is the process of eliminating the unbalanced force. There are three common iterative methods: Newton-Raphson method; Modified Newton method; Quasi Newton method. The advantages of iterative method are simple and easy, which is suitable for non-linear problems and general geometric nonlinearities. The second is the incremental method. The basic idea of incremental method is to linearize the nonlinear problem by using the load increment. The last one is the hybrid method. If the same nonlinear system is mixed with the increment method and iteration method, it is called the mixed method or progressive iteration method. The incremental Newton-Raphson method, or Euler-Newton method, is adopted in ANSYS nonlinear finite element analysis software.

B. Representation of the Catheter

In cardiovascular surgery, the catheter may bend in the vessel [20]. In our Intervention robot, the catheter will buckle slightly in the catheter guiding sleeve. This deformation will lead to decline of the position control precision.

Catheter is a long and thin surgical instrument, and its model can be built by 1D elastic rods [21]. In order to use the Cosserat theory of elastic rods, the catheter should be discretized into N spatial control points. As is shown in Fig.4.

The method of Lagrange multipliers is used to maintain the inextensibility of the catheter in this catheter model.

In the following simulation, the behavior of the catheter in the sleeve is analyzed using the elastic rod model and the finite element method.

Ⅳ. EXPERIMENT

A. ANSYS simulation environment

ANSYS software is a large general finite element analysis software developed by ANSYS Inc. It is the fastest growing Computer Aided Engineering (CAE) software in the world, capable of sharing and exchanging data with most of the computer-aided design (CAD) software. Its analysis type includes structural static analysis, structural dynamics analysis, structural nonlinear analysis, thermodynamic analysis, electromagnetic field analysis, fluid dynamics analysis, sound field analysis, piezoelectric analysis and etc. ANSYS has multiple physical field optimization functions, nonlinear analysis functions and various solvers, which are applicable to different problems and different hardware configurations. The software consists of three parts: pre-processing module, analytical calculation module and post-processing module. The research in this paper will use these three sections. ANSYS analysis flow chart is shown in Fig. 5.

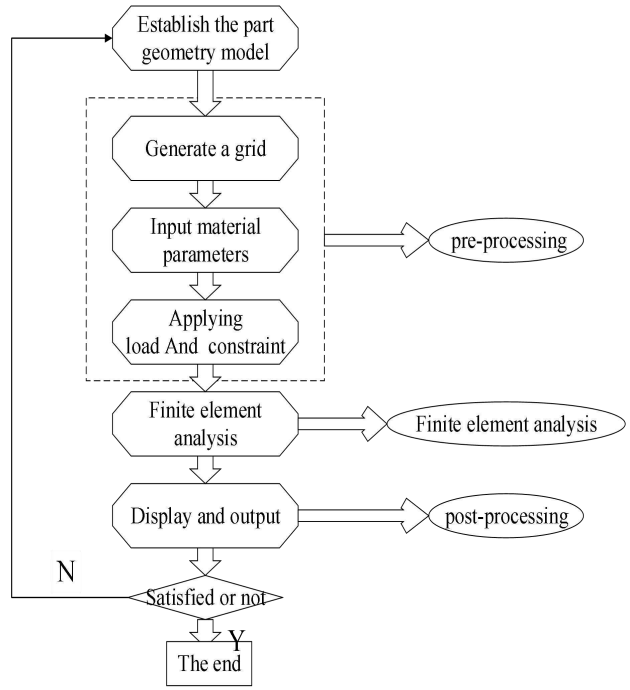


Fig. 5. ANSYS analysis procedure.

B. *Physical Modeling*

Prior to analysis, the building of physical model of the catheter and sleeve is required. In this paper, ANSYS DesignModerler module is used to establish a two-dimensional geometric model of catheter and sleeve. The catheter model is based on the theory of elastic rod theory.

According to the actual size of the sleeve in Fig. 3 and catheter in Fig.6, the geometric model is established based on the ANSYS DesignModeler as Fig. 7. Among them, the 3D model is simplified as a two-dimensional model, because our simulation experiment focuses on the change of catheter length caused by the catheter bending, and the two-dimensional change is enough. Moreover, three-dimensional

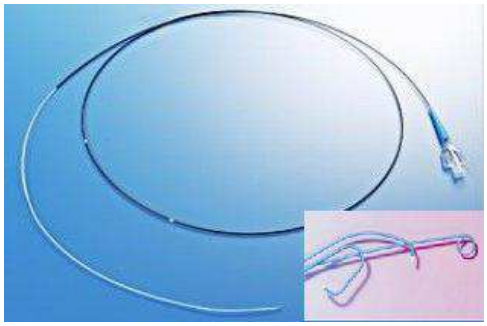


Fig. 6. Catheter using in the interventional surgery.

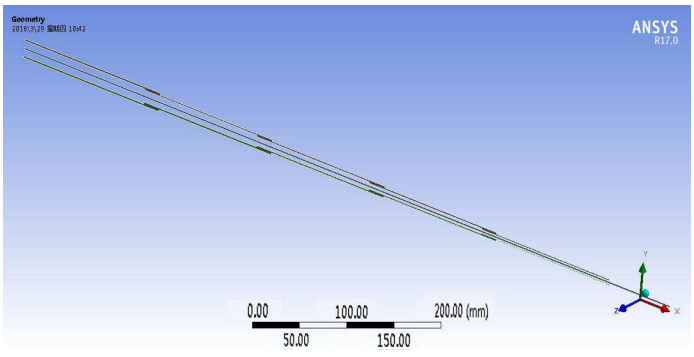


Fig. 7. Geometrical model of catheter and sleeve in ANSYS.

analysis tends to cause non-convergence.

In addition, in the process of Interventional surgery by our robots, the length of the sleeve is constantly changing with the movement of the sliding block, and there is an approximate frictionless sliding between the various parts of the sleeve. In our simulation, the simulation type is a nonlinear static structure analysis. The length of the sleeve has not be changed in real time, moreover, the change in sleeve's length is complex and changeable without law in the surgery. Thus it is difficult to make dynamics simulation. So choose several different sleeve lengths to simulate. Fig. 7 is the model diagram of the sleeve extension to the longest.

C. The simulation of the catheter

After the geometric model was established, we began to implement nonlinear structural statics simulation. The first step is to set the unit type and material properties of the catheter and the sleeve model. The common materials used for catheters are polyethylene, polyvinyl chloride and nylon [22]. The material for the sleeve is also polyethylene (PE), so our model is set to polyethylene. Since there is no PE material in the common material library of ANSYS, the custom material PE is defined and set the elastic modulus, Poisson's ratio and other parameters, as the Table I shows. Besides, because of the nonlinearity of the catheter and the two-dimensional simulation, the unit type is set to PLANE182 considering that this unit is able to simulate nonlinear phenomena.

Afterwards grid is generated. This step is not complicated because the ANSYS workbench module has the capability of

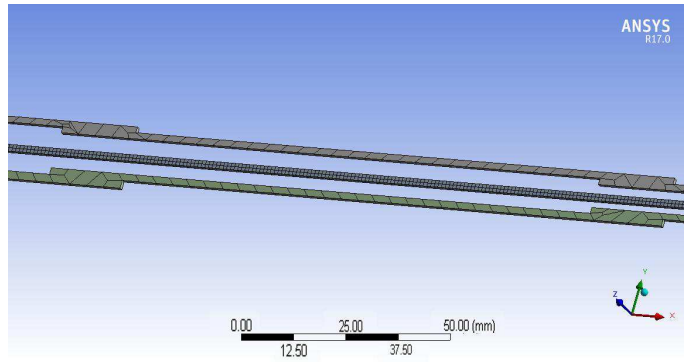


Fig. 8. Part of the grid of the catheter and sleeve.

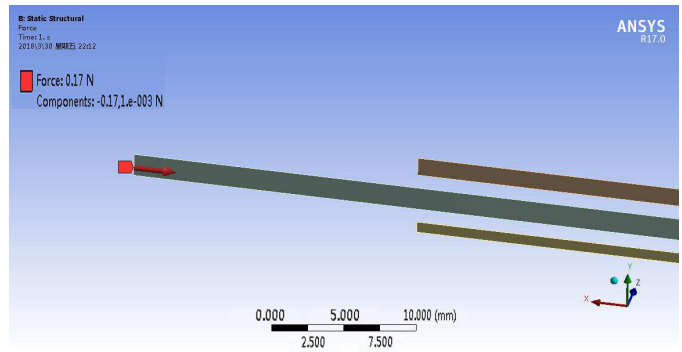


Fig. 9. Force applied to the catheter.

TABLE I
THE MATERIAL PROPERTIES OF PE

	Elastic modulus	Poisson's ratio	Mass density
PE	1.72E+08N/ m^2	0.439	9.17E+02Kg/ m^3

automatic grid partitioning. However, due to the small size of the catheter, it is necessary to constantly adjust the mesh size to adapt to the next deformation simulation. Part of the resulting grid is shown in the Fig. 8.

The third step is to apply load and constraints. The boundary of the sleeve and the end of the catheter are fixed, then the force of different gradient which simulate according to the operation habit of doctor is applied to the tip of the catheter. The applied force is shown in Fig. 9. In addition, the length of the sleeve is changed with the motion of the robot. In our simulation, the process is simplified and several different sleeve lengths are selected for simulation. Finally, the deformation of the catheter in the sleeve during the push process is obtained.

V. RESULTS AND DISCUSSION

Based on actual data [23], the force that the doctor applied to the catheter is between 0.1N and 0.2N during the process of interventional surgery. Thus in our simulation experiment, different forces are applied to the head end of the catheter to obtain the deformation results. At the same time, the length of

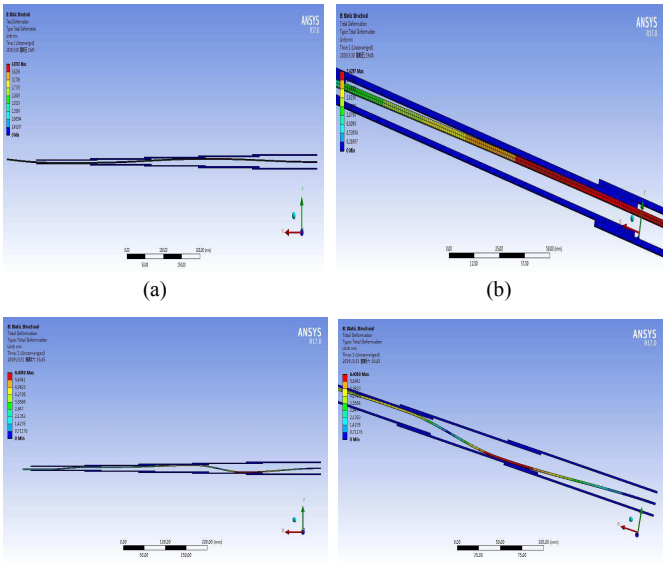


Fig. 10. Catheter deformation under different conditions: (a) the catheter deformation in 770mm sleeve, 0.2N; (b) amplification view of (a); (c) The catheter deformation in 690mm sleeve, 0.2N; (d) amplification view of (c).

the sleeve is another independent variable. Fig. 10 is two of the deformation result graph of the catheter when the force applied to the catheter.

It can be observed from the figure that in the process of pushing the catheter, there is still a large nonlinear deformation under the restraint of the sleeve because the catheter is a flexible object. Fig.10. (a) is the simulation result when the force is 0.2N and the sleeve length is 770mm, and (b) is a part of the enlarged image. Fig.10. (c) (d) is the deformation result graph of the catheter when the force applied to the catheter at 0.2N and the sleeve length is 690mm.

Fig.10 shows two examples of catheter deformation. The following table is the displacement caused by the catheter's deformation with the change of two independent variables: the force of the doctor pushing the catheter and the change of the telescopic length of the sleeve.

TABLE II shows the deformation degree of the catheter decreases with the decrease of the telescopic length of the sleeve when the force is the same. And the larger the force, the greater the deformation. In addition, as shown in the Fig.11, when the force is especially large, there will be plenty of deformation affecting the accuracy of control.

The simulation results obtained the quantized displacement error causing by the catheter deformation. The maximum displacement error reached 4mm while the desired position control accuracy of the robot system is less than 1mm. The obtained displacement error can be added to the control compensation algorithm for compensating the error and improving control accuracy when our RVIR implement surgery. In addition, the bad catheter deformation when operating force is unusually large indicates that our

TABLE II
THE DISPLACEMENT ERROR CAUSED BY DEFORMATION OF THE CATHETER

Sleeve length		770 (mm)	690 (mm)	490 (mm)	290 (mm)
Force	0.1N	2.4297	1.6461	1.3428	0.8989
	0.2N	4.0767	3.5588	1.6370	1.6259

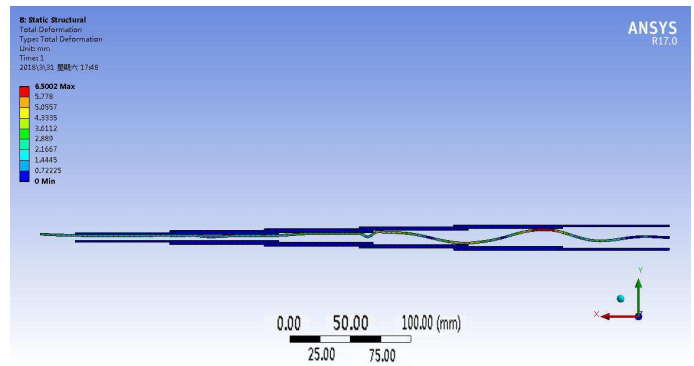


Fig. 11. Deformation of catheter in too large force.

intervention robot needs the force feedback function to reduce the risk of interventional operation and improve the accuracy of control.

VI. CONCLUSIONS

In this paper, we analyzed the catheter deformation kinematics in the sleeve of the interventional surgical equipment designed based on the ANSYS. Geometrical modeling of catheter and sleeve has been established and FEA was performed in ANSYS. Afterwords, the displacement error of the position control caused by catheter deformation was obtained. The specific catheter deformation was affected by two factors, namely the length of the sleeve and the push force of the catheter. Through the simulation data of ANSYS, we found that the length of catheter length varies from 0mm to 4mm during operation. The simulation results make a prediction about the actual deformation of catheter, and prepare for the future error compensation work for the safety of clinical operation.

However, there are still several drawbacks in this research. Firstly, only several different sleeve lengths are selected for simulation instead of all the length, so the specific mathematical relationship between catheter deformation, sleeve length and the force are not yet obtained. Secondly, this research has not analyzed the influence of catheter deformation on the detection force accuracy.

The simulation analysis is only the preliminary work. In the future, the specific mathematical relationship between catheter deformation, sleeve length and the force will be obtained in the experimental analysis. In addition, the compensation algorithm should be designed and added to the control algorithm to compensate the position and force error caused

by catheter deformation, and further to improve the control precision and force feedback accuracy.

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