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Design of A Novel Virtual Sensor for the Vascular Interventional Robotic System

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***Abstract* –In order to solve existed problems in the force measurement part of vascular interventional surgical robots. In this paper, A new concept was proposed to obtain more accurate force information and solve the problems of traditional sensors in vascular interventional surgery. This sensorless measurement is based on kinematic equations in robotics. First of all, the virtual sensor mentioned in this paper firstly collects the pictures of the catheter in the blood vessel, extracts the deformation variables, then establishes the catheter kinematics model, and imports the extracted deformation variables into the catheter kinematics model. The final output force value. Finally, experimental results showed that force measurement in this way can avoid the problem of sterilization caused by the sensor entering the blood vessel and the problem of insufficient accuracy caused by indirect measurement.**

Index Terms - Kinematic equation, Virtual sensor, Vascular interventional surgery

I. INTRODUCTION

For the current force measurement of vascular interventional surgery robots, there are two main methods. One method is to directly measure the force by installing sensors on the catheter. In the direct measurement part, for the impact force at the front end of the catheter, most of them use fiber optic pressure sensors for measurement. Its outer diameter is only 1 mm, its length is 4 m, and it is covered with PTFE (polytetrafluoroethylene), which can easily pass through the catheter. Cavity measurement, can be used repeatedly, and has electromagnetic compatibility, but the highest sampling frequency is only 250 Hz. The interaction between the side wall of the catheter and the vessel wall is measured by covering the side wall of the catheter with conductive rubber and using its piezoresistive effect [1]. After the optical fiber and the conductive rubber sensor's measurement signal are processed by subsequent circuits, they are all output with an analog voltage value of 0 to 5 V. The host computer reads two measurement signals by multi-thread technology and AD acquisition card.

In the indirect measurement part, it is often measured by the displacement or thrust of a part of the structure caused by the catheter touching the blood vessel wall, as described in [2].

Our laboratory's experimental platform for vascular interventional surgery robots is divided into master and slave. The following problems apply to the directly mounted sensors.

1). Whether it is an optical fiber or a conductive rubber sensor, there is a problem of sterilization the sensor entering the blood vessel during the surgery.

2). Low portability. Nesting the sensor in the catheter part needs to consider whether the catheter part meets the installation of the sensing element. The difference in various parameters such as the model between different catheters will affect whether it can successfully achieve force measurement.

3). The measurement signals of the optical fiber sensor and the conductive rubber sensor are all electrical signals. During the processing of the electrical signals, there are problems such as low signal-to-noise ratio and local distortion, which affect the requirements for high accuracy in vascular interventional surgery robots.

The indirect measurement part has the following problems:

1). The problem of friction: There is friction between the external parts that cannot be solved.

2). The slide rail raises the so-called frictionless problem, which has the problem of being unable to be fixed.

3). The force at the end of the direct catheter cannot be measured.

There are great defects in physical sensors or physical measurements in vascular interventional procedures that require high accuracy, and it brings certain limitations to the further development of this field in the future [3]. Therefore, a measurement method for obtaining force using catheter modeling is proposed. In the virtual sensor system proposed in this paper, the image obtained by the camera is directly passed to the PC for processing. The traditional physical sensor needs to have a signal processing link, which is the advantage of the virtual sensor system. In addition, the virtual sensor does not need to enter the blood vessel when measuring the force, so this also solves the above-mentioned problems related to sterilization.

II. OVERVIEW OF THE PLATFORM

The master-slave manipulator is the master-side manipulator operated by the doctor, which transmits the doctor's surgical actions to the slave through communication[4-5].After receiving the doctor's action information sent by the master,

the client implements the corresponding action. The slave uses a stepper motor to operate the catheter.[6] The operating master transmits the master's actions to the slave through the serial port. After receiving signals from the stm32 microcontroller, the slave drives the stepper motor to move the catheter [7].

The method of virtual force measurement proposed in this paper is mainly divided into several parts. The design diagram of the virtual sensor is shown in Fig 1. The Fig2 shows the vascular interventional surgery robots system in our laboratory.In Fig.2, (a) is the master manipulator of the laboratory platform, and (b) is the slave equipment.

First, we need to get the current catheter position when importing the kinematics model of the catheter to get the dynamic parameters required by the D-H parameter table in the kinematics model. Therefore, the first part is image processing. In this paper, the contour of the catheter is extracted using edge detection, the points of the contour of the catheter are extracted, and the least square method is used for image fitting to obtain the bending angle of the catheter. The second part is the establishment of the kinematics model of the catheter. Take a small section of the catheter and approximate the rigid body of each section to get the joint equivalent to the manipulator. As shown as Fig3.

It is most appropriate to select 0.14cm for each section [2]. The force Jacobian matrix of the catheter, so as to obtain the corresponding force value. Finally, the calculated force value is displayed in real time in Matlab after the calculation, and the curve of the change in stress value is drawn.

In the other part, the current force sensors in the laboratory are used to measure the impact force for comparison. After the catheter hits the vessel wall, a backward thrust is generated, and the corresponding force is measured. After the force data is measured, it is transmitted to the single-chip computer through A / D conversion. The single-chip computer is connected to the PC using a serial port. The corresponding force information is displayed through the serial port assistant and the corresponding force changes are plotted.

Finally, the measured forces are compared to obtain experimental data port. The corresponding force information is displayed through the serial port assistant and the corresponding force changes are plotted.

Therefore, the virtual sensor part mentioned in this article is mainly divided into three parts. The first step is image processing. The image processing of the catheter is to provide parameters for the subsequent mathematical model. The second step is the establishment of the catheter kinematics model. The third step is the processing and output of the force value.

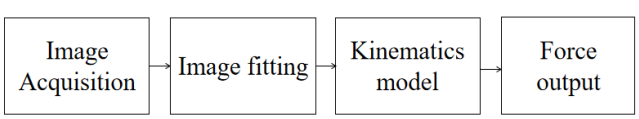
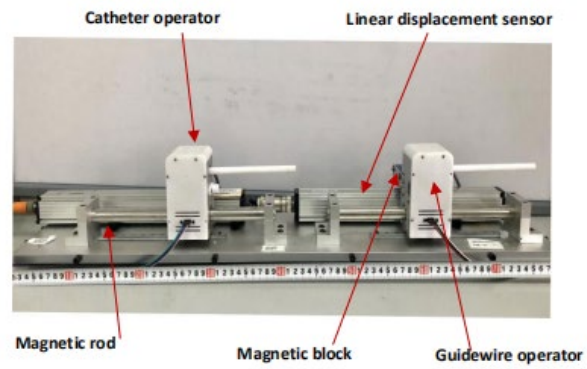
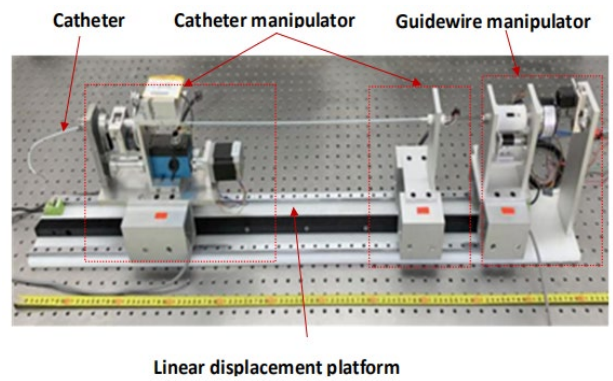


Fig 1 Working flow chart of virtual sensor



(a). The master manipulator



(b). The slave equipment

Fig 2 Manipulators of vascular intervention surgery robot

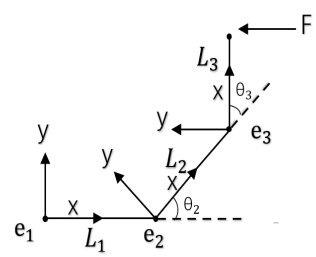


Fig 3 A schematic diagram of the discrete guide wire's bending under Force

III. THE WORK OF CATHETER IMAGE DATA EXTRACTION

In this paper, the pictures obtained from the DSA medical map are imported into the computer in real time, and the imported pictures are processed in the computer. First of all, the shape of the human body and the catheter in the human body is processed. First, the image needs to be processed by local adaptive binarization to extract the catheter part. Then perform edge detection on the extracted catheter, extract the contour of the catheter, and then use the image to extract the contour of the extracted contour to extract the deformation variables generated after the catheter hits the vessel wall and record it as θ , θ Values are important

parameters in the catheter kinematics model. The entire image processing is divided into the following sections:

A. Local adaptive binarization

The pictures we get in the medical map during the surgery are pictures of the patient's body and the catheter, but only the catheter part is needed in this paper, so the image needs to be adaptively binarized. Binarization is very important in the entire field of image processing [8]. The elements of each part of an image often have different pixels. In the image, we need to select an appropriate threshold to extract the part we want[9]. The processing idea of binarization is that assuming that the gray level range of a gray image is (0,255), the gray value of the image is $f(x,y)$, $f(x,y)\in\{1,2,...,255\}$.

Let the threshold be $T(0\le T\le 255)$,then

$$g(x,y)=\begin{cases}0 & f(x,y)<T\\ 1 & f(x,y)\ge T\end{cases} \tag{1}$$

The threshold selected in this article is 145.

Among them, $g(x,y)$ is the value of each pixel point in the binarized image. if $g(x,y)=1$, it indicates that the point is the target, and if $g(x,y)=0$ indicates that the point is the background [10].

B. Edge detection

In the design of this virtual sensor, the canny algorithm must be used. Because the canny algorithm uses first-order differential operators to extract edges, the edge positioning is not very accurate, and the edge of the image is more than one pixel[11]. Noisy, real weak edges can be detected. For our vascular interventional surgery, the required accuracy is relatively high, and accurate catheter contours must be obtained in order to accurately fit the curve. The advantage of the canny method is that two different thresholds are used to detect the strong edge and the weak edge, and only when the weak edge and the strong edge are connected, the weak edge is included in the output image. Therefore, in this thesis, the canny method is used for edge extraction [12].

Canny method extraction has the following steps. The first is Gaussian smoothing. The purpose of filtering is to remove noise. The core formula of Gaussian filtering is shown below:

$$H_{ij}=\frac{1}{2\pi\sigma^2}exp\left(-\frac{\left(i-(k+1)^2\right)+\left(j-(k+1)^2\right)}{2\sigma^2}\right) \tag{2}$$

i and j must meet $1\le i;\ j\le(2k+1)$. The second step needs to calculate the gradient intensity and direction. The most important thing in edge detection is the sharp change of the characteristic gray value. The change of the gray value is generally expressed by the derivative of the binary function. Since the image is discrete data, the derivative can be represented by a difference value, and the difference is the gray difference in actual engineering. The operator calculates the gradient in the form of image convolution. The gray values in different directions are as follows:

$$g_x(m,n);g_y(m,n) \tag{3}$$

$$G(m,n)=\sqrt{g_x(m,n)^2+g_y(m,n)^2} \tag{4}$$

$$\theta=arctan\frac{g_x(m,n)}{g_y(m,n)} \tag{5}$$

The third step needs to filter the non-maximum value. During the Gaussian filtering process, the edges may be enlarged [13]. This step uses a rule to filter points that are not edges, so that the width of the edges is as large as 1 pixel: if a pixel belongs to the edge, then the gradient value of this pixel in the gradient direction is the largest. Otherwise it is not an edge and the gray value is set to 0. The formula is as follows:

$$M_T(m,n)=\begin{cases}M(m,n) & M(m,n)>T\\ 0 & M(m,n)\le T\end{cases} \tag{6}$$

Finally use upper and lower thresholds to detect edges[13].

The experimental environment used in this paper is the glass vessel. In the process of distinguishing between the catheter and the glass vessel, the image processing technology used is local adaptive binary processing. Because the color of the catheter and the glass vessel is different, the adaptive algorithm can choose the corresponding threshold according to the environment and convert the catheter image.

C. curve fitting

The slope information is obtained by interpolation sampling, and the slope information is transmitted to the parameters in the catheter kinematics model.

The curve fitting part uses the least square method.For a given set of data points $\{(X_i,\ y_i)\}(i=0,1,2,...,\ m)$,In the given function class. φ to find $p(X)\in\varphi$ and minimize the sum of squared errors. In a geometric sense, it is to find the curve y = p (x) with the smallest sum of the squared distances from the given point set $\{(X_i,\ y_i)\}(i=0,1,2,...,\ m)$. The function p (x) is called the fitting function or the least square solution [14]. Find the fitting function p (The method of x) is called the least square method of curve fitting. The calculated error can be calculated by subtracting the actual value from the theoretical value [15].

IV. KINEMATIC ANALYSIS OF THE CATHETER

In the vascular interventional surgery robot, the doctor operates the master side, transmits the action signal to the

slave side through communication, and the slave side performs corresponding operations on the catheter. The catheter chosen in this paper is a general-purpose catheter for medical use, because the part of the catheter that touches the vessel wall is the closest to the vessel wall.

Firstly, the coordinates of the catheter were established. According to the concept of the generalized force at the end of the force Jacobian, the deformation of the catheter was caused by the collision with the vessel wall. Therefore, the end of the catheter was selected as the geodetic coordinate system, and then its own coordinate system was established. According to the rules for establishing the coordinate axis, the prescribed direction is along i-1 and i the common perpendicular direction of the sum Z_0 and Z_1 are coaxial[16].Find the intersection of the common vertical lines of i-1 and i and i-1 as the origin of the coordinate system. The specified axis is along the direction of the common vertical line of i-1 and i. When the two axes intersect, it is perpendicular to the joint axis i-1 and the plane i on which it lies. Axis When the two axes intersect, they are perpendicular to the joint axis i-1 and i the plane on which they lie. This variable Y_{i-1} should meets the right-hand rule $Y_{i-1}=Z_{i-1}\times X_{i-1}$ Then the parameters of the connecting rod are determined, and the D-H parameter table is established. The four parameters of the D-H parameters are a_{i-1}, α_{i-1}, d_i, and θ_i. a_{i-1} is the distance along axis X_{i-1} from Z_{i-1} to Z_i α_{i-1} is the angle along axis X_{i-1} from Z_{i-1} to Z_i. d_i is the distance along axis Z_i from X_{i-1} to X_i θ_i .is the angle along axis Z_i from X_{i-1} to X_i.

According D-H parameter table rules, the D-H parameter table can be established according to the rules of robot kinematics. The joint axes selected in this paper are five axes in total, and the distance between each joint is 0.14cm. The D-H parameter table is obtained as shown below:

TABLE I

CATHETER D-H PARAMETER TABLE

i	a_{i-1} (mm)	α_{i-1} (°)	d_i (mm)	θ_i (°)
1	0	0	0	θ_1
2	140	0	0	θ_2
3	140	0	0	θ_3
4	140	0	0	θ_4
5	140	0	0	θ_5

The kinematic equation of the catheter is

$$x=L_1+L_2\cos_2+L_3\cos_{23} \tag{7}$$

$$y=L_2\sin_2+L_3\sin_3 \tag{8}$$

Differentiate the time t respectively to obtain the Jacobian matrix and the force Jacobian matrix.

$$J^{\mathrm{T}}(q)=\begin{pmatrix} -140\sin(2+3)-140\sin(3) & -140\sin(2+3) \\ 140\cos(2) & 140\cos(3) \end{pmatrix} \tag{9}$$

The so-called force Jacobian matrix is that when the catheter interacts with the external environment, a force f and a moment n are generated at the place of contact, collectively referred to as the terminal generalized (operating) force vector and then record it.

$$F=\begin{bmatrix} f \\ n \end{bmatrix} \tag{10}$$

$$\tau=\left[\tau_1,\tau_2\cdots,\tau_n\right] \tag{11}$$

$$\tau=J^{\mathrm{T}}(q)F \tag{12}$$

For the n-joint catheter, the stiffness of each joint is set to kqi, (i = 1,2,⋯, n), and the external deformation is X under the action of external force F, and the elastic deformation of each joint is dqi (i = 1, 2,⋯ , n). Then there are:

$$\tau_i=k_{qi}dq_i,\quad i\in(1,\ n) \tag{13}$$

Among them, is the joint moment, also known as the static error moment.

The above formula is written in matrix form:

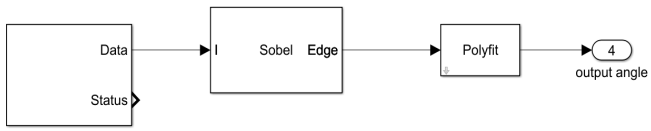
$$\tau=K_q dq \tag{14}$$

$$q=[dq_1,dq_2,\cdots dq_n]^T \tag{15}$$

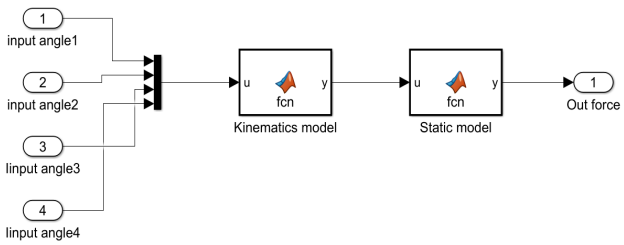
$$K_q=diag(k_{q1},k_{q2},\cdots k_{qn}) \tag{16}$$

V. KINEMATIC MODEL SIMULATION

The kinematics model of the catheter was built by Simulink. The Simulink simulation diagram of the catheter is shown as Fig4. As shown in (a) in Fig 4, it is divided into the original image acquisition module, the edge detection module and the curve fitting module. The final output angle is used as the input of (b) in Fig. 4. Fig 4(b) transmits the output result in (a) to the kinematics module, and then puts it into the statics module to output the final force value. The data graph of the simulated value of the rotation angle of the catheter and the actual fitted value is shown as Fig 5 and Fig 6. As shown in Fig 5 and Fig 6, there is an error between the theoretical fitting angle value of the simulation result and the actual value. Because the fitting order selected by matlab is too high during fitting will cause the angle output to be difficult to handle, so this part of the error exists because the part selected by the catheter when building the model is a local small part of the catheter tip Therefore, the error of this part is still in the field of medical safety. The maximum error of θ_2 is 2.8°, the minimum error is 0.2°. The maximum error of θ_3 is 4.3°, the minimum error is 0.7°.



(a). the simulink simulation diagram of image processing



(b). the simulink simulation diagram of catheter kinematics model

Fig 4 The simulink simulation diagram of virtual sensor

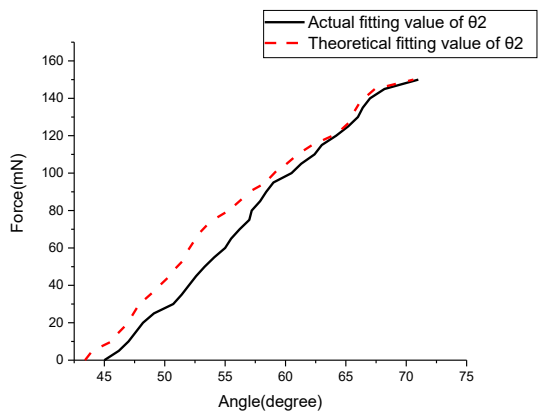


Fig 5 Catheter angle of θ_2 transformation map

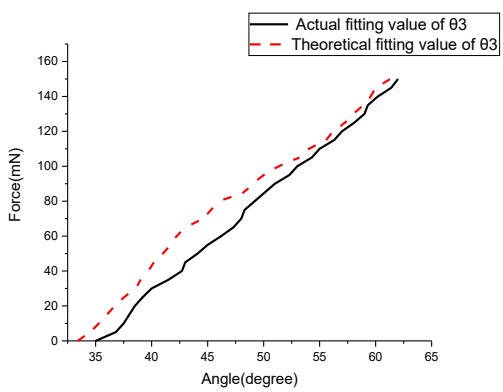


Fig 6 Catheter angle of θ_3 transformation map

V. Experiments and Results

A. The experimental set up

The part of the experimental platform is divided into a master-side manipulator, a slave-side manipulator, a camera, a PC, and a person operates on the master-side, and the slave-side takes corresponding actions accordingly. Using the camera to capture the catheter image, and display the corresponding force value on the PC side through the kinematic model conversion. The experimental platform is shown in the Fig7. Because the force part is concentrated on the tip of the catheter, the part that is too far from the collision point will not affect the overall force. Therefore, in the process of experimental design, the three points closest to the glass vessel wall were selected as joint points.

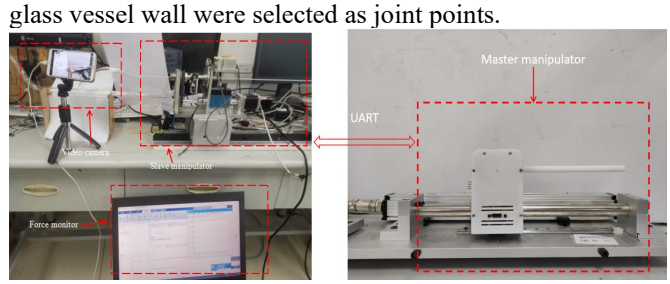


Fig7 Experimental platform diagram

B. The experimental results

In determining the accuracy, the measured values of 0%, 20%, 40%, 60%, 80% and 100% of the full scale are selected for error analysis. As shown in formula 14. δ is the accuracy. Δ_{max} is the maximum error. A_{max} is full scale. Therefore, the maximum error shown is 12mN and full scale is 160mN in the table 2, Since the accuracy level can only be 0.2, the calculated accuracy is 0.075. According to the standards based on sensor accuracy.[17] So the accuracy of the virtual sensor is 0.1.

$$\delta = \frac{\Delta_{max}}{A_{max}} \tag{14}$$

According to $F - f = ma$, a is the acceleration, F is the thrust of the slave manipulator, and f is the friction of the catheter in the glass vessel. Since doing a constant motion a =0, therefore $F = f$. So the results obtained needs to subtract f . The experimental result obtained f is 8mN.

TABLE II

Error Measurement Table

The percentage of full scale(%)	The force value of each range (mN)	Force value measured by virtual sensor(mN)	Error (mN)
0	0	0	0
20	33	30	3
40	64	59	5
60	95	89	6
80	128	116	9
100	160	148	12

In the experiment, the calibration between the angle and the force value is shown as Fig8. Importing different angles into the catheter kinematics model established by matlab to get the corresponding force information. The detecting results of virtual sensors is as Fig 8. The values of θ_2 and θ_3

correspond to the force values one by one. As can be seen from Fig 9.

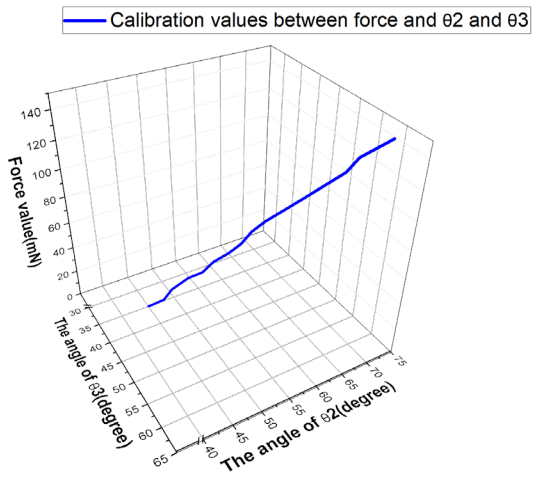


Fig8 Calibration of the force value of catheter deformation

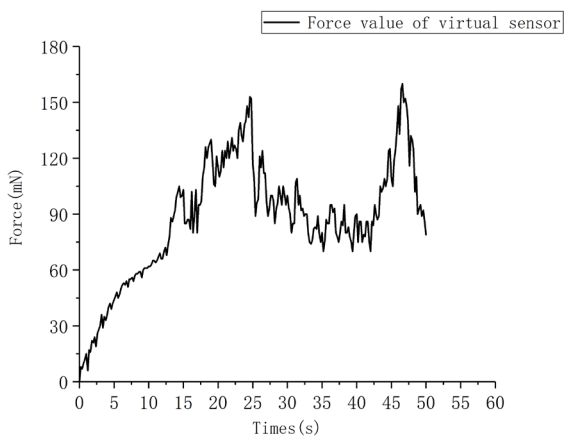


Fig9 Measurement results of virtual sensors

VI. Conclusions and Future Work

In this paper, a mathematical model of the correspondence between the deformation of the catheter and the force is proposed. Through this mathematical model, a virtual sensor is designed. This virtual sensor can not only solve the problem of sterilization. when the physical sensor enters the blood vessel, but also solve the problem of insufficient accuracy caused by some indirect force measurement methods.

Acknowledgements

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