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Design of a Surgeon's Controller for Catheter Navigation

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Abstract —**Endovascular intervention is expected to become increasingly popular in medical practice, both for diagnosis and for surgery. Accordingly, researches of robotic systems for endovascular surgery assistant have been carried out widely. Robotic catheter navigation systems are with advantages of higher precision, can be controlled remotely etc. However, the haptic feelings, the important function for propelling robotic catheter navigation system is immature. In the paper, a robotic catheter navigation system is proposed. The navigation system is designed to simulate the surgeons operating procedure. And the haptic feedback issue is concerned. A surgeon's controller is developed. Therefore, surgeons can carry out operation with their own skills. System implement and performance are presented. System implement and performance are presented.**

Index Terms **— Catheter navigation system, surgeon's controller**

I. INTRODUCTION

Endovascular intervention is expected to become increasingly popular in medical practice, both for diagnosis and for surgery. However, as a new technology, it requires a lot of skills in operation. In addition, the operation is carried out inside the body, it is impossible to monitor it directly. Much more skills and experience are required for doctors to insert the catheter. In the operation, for example the catheter is inserted through patients' blood vessel. Any mistakes would hurt patients and cause damages. An experienced neurosurgery doctor can achieve a precision about 2mm in the surgery. However, the contact force between the blood vessel and the catheter cannot be sensed. During the operation an X-ray camera is used, and long time operation will cause damage to the patient. Although doctors wear protecting suits, it is very difficult to protect doctors' hands and faces from the radiation of the X-ray. There are dangers of mingling or breaking the blood vessels. To overcome these challenges, we need better technique and mechanisms to help and train doctors. Robotic system takes many advantages of higher precision, can be controlled remotely etc. However, compared with hands of human being, none of a robotic system could satisfy all of the requirements of an endovascular intervention. Not only because the machine is not as flexible as hands of human being but also lacks of touch. In any case, robotic catheter manipulation system could provide assistant to surgeons in the operation, but it has a long way to go to replace human being.

Products and researches are reported in this area. One of the popular products is a robotic catheter navigation system called Sensei Robotic Catheter System supplied by Hansen Medical [1]. The Sensei system provides the physician with more stability and more force in catheter placement with the Artisan sheath compared to manual techniques, allows for more precise manipulation with less radiation exposure to the doctor, and is commensurate with higher procedural complications to the patient. Because of the sheath's multiple degrees of freedom, force detection at the distal tip is very hard.

The Stereotaxis Inc. developed a magnetic navigation system: the Niobe [2]. The system facilitates precise vector based navigation of magnetically enabled guide wires for percutaneous coronary intervention (PCI) by using two permanent magnets located on opposite sides of the patient table to produce a controllable magnetic field. Catheter Robotics Inc. has developed a remote catheter system called Amigo [3]. This system has a robotic sheath to steer catheter that is controlled at a nearby workstation, in a manner similar to the Sensei system. Yogesh Thakur et al. [4] developed a kind of remote catheter navigation system. This system allowed the user to operate a catheter manipulator with a real catheter. So surgeon's operative skills could be applied in this case. The disadvantage of this system is lack of mechanical feedback. T. Fukuda et al. [5] at Nagoya University proposed a custom linear stepping mechanism, which simulates the surgeon's hand movement. Regarding these products and researches, most concerns are still the safety. Force information of the catheter during the operation is very important to ensure the safety of the surgery. However, measurement of the force on catheters is very hard to solve in these systems. A potential problem with a remote catheter control system is the lack of mechanical feedback that one would receive from manually controlling a catheter [6]-[10].

Our group has developed kinds of robotic catheter navigation system in resent years. A wheel-driven catheter manipulator was made [11] [12]. In the system, phantom omni was employed as the surgeon´s console. Force sensors are r installed on the end-tip of the catheter. In the system user can monitor force information by using monitors. However, compare with some other system problems of this system are poor operability and lacks of vivid haptic feedback [13].

In order to improve these existed problems we developed a novel robotic catheter navigation system that imitates surgeon´s action to operate catheter [14]. Surgeon´s consoler is proposed. With the system dexterous operation and good operability can be achieved. On the other hand, force feedback is a major concern of this system. Implementation of the force feedback contains two key technique issues, force measurement and haptic implement. Additionally, compactible virtual reality environment is made as an assistance system to help users carry out their procedure [15].

In this paper, a design of surgeon's controller for operating catheter and guide wire is proposed. The remainder of this paper is organized as follows. In the next section the design motivation is introduced. Following that, in Section III Kinematic of the System is discussed. The next section is presents concluding remarks.

II. DESIGN MOTIVATION

In the catheter-based operation, there are two basic motions of the catheter, rotation, and go forward and backward. Therefore, the surgeon could finish an operation just by operating the catheter with these two basic motions. Figure 1 shows the surgeon's actions during inserting motion.

In a real operation procedure, surgeon inserts the catheter to the lesion based on the hand's feeling. For example, the surgeon rotates the catheter when he/she feels more resistance from the catheter. Some time the surgeon operates the catheter based on the DSA image but most of the time the surgery carries out the operation based on the hand feeling. Haptic is the essential element for surgeons to finish operations.

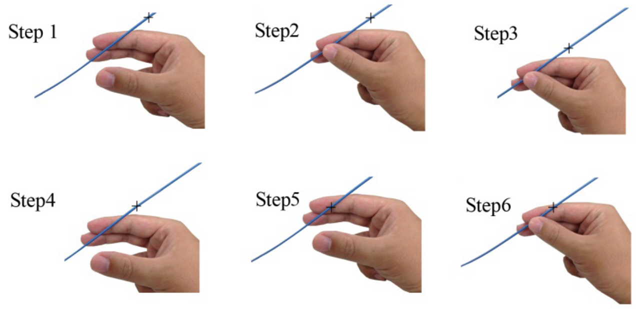

Figure 1 Catheter Operation Process

We designed a surgeon's controller for operating catheter and guide wire. The mechanism is the slider crank mechanism. Surgeons can input their control commands to the catheter manipulator and get haptic feedback with the proposed device. Figure 2 shows the schematic of the acquisition of the hand's motion. Handle are placed on the joint C, it is driven moved along a straight line perpendicular to the X-axis and can be rotated with Y-axis. The angle of joint A and joint B are controlled by two motors with encoders. The displacement of handle and the force feedback will achieved by control the transformations of the θ_1 and θ_2.

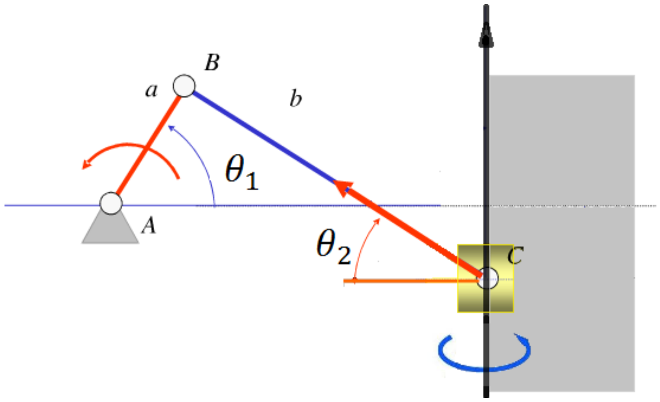

Figure 2 Acquisition of the Hand's Motion

The catheter manipulator is shown in Figure 3. We designed this mechanism with imitating surgeon´s hands. Grasper 1 in figure 3 is using for fixing catheter on the cylinder playing the role of the thumb in Fig. 1. One can operate the catheter to insert and rotate when the catheters fixed on the cylinder with grasper 1. And one can drive the mechanism go backward without disturb the catheter by lifting up grasper 1 and putting down grasper 2.

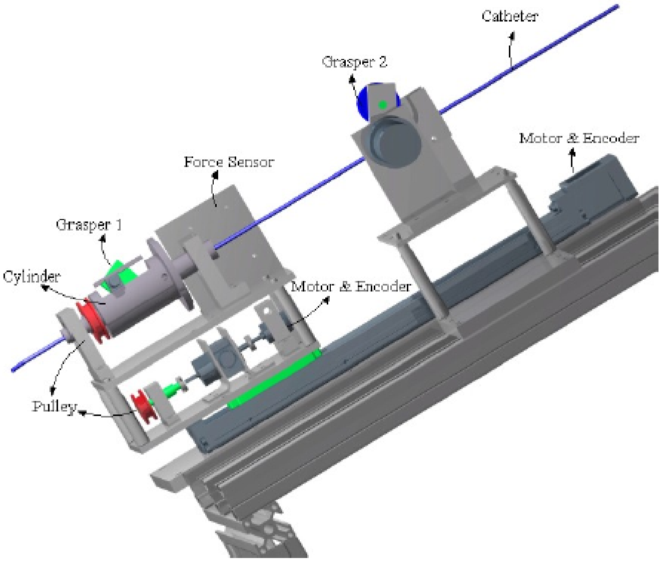

Figure 3 The Catheter Manipulator

A Maxon dc motor coupled to the cylinder drives rotation of the catheter. The translation is driven by a movement stage also connected to the cylinder. Control of the system is realized by a digital controller(TI, TMS320F28335). In the future a more compact structure that will keep a same action principle will be developed.

III. KINEMATIC OF THE SYSTEM

The movement of mechanism in two degrees of freedom can be achieved by using parallelogram structure. Figure 4 shows design of surgeon's controller.

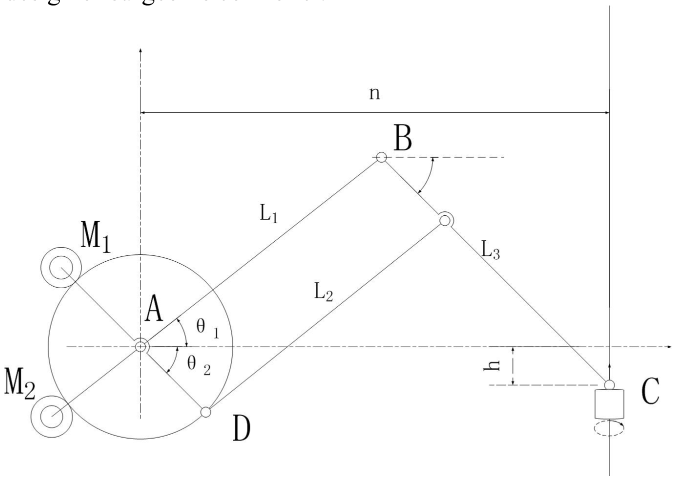

Figure 4 Modelling of the System

With point A as a origin coordinates, coordinate system is established, the horizontal and vertical direction are respectively X, Y axis. The θ_1 is the angle between X-axis and bar AB, and θ_2 is angle between X-axis and bar BC. Two motor M1 and M2 connect with bar AD and bar AB. M1, M2 and a wheel are composed of two independent planetary gear trains. Their function is controlling θ_1 and θ_2, and controlling the displacement of handle and the force feedback using transformations of the θ_1 and θ_2. The handle linked to the joint C. The joint C can push or pull the handle and make the handle rotated freely. L_i (i=1,2,3) represent length of three member bar, and $L_1 = L_2$. ***n*** is the distance between the Y-axis and movement orbits of the handle, it is a given value. And the ***h*** is the distance between the X-axis and the handle.

Using method of calculation vector, the relationship with the θ_1, θ_2 and position of handle ***P*** are defined by:

$$P = (x_c, y_c), \left\{ \begin{array}{l} L_1\cos\theta_1 + L_3\cos\theta_2 = x_c \\ L_1\sin\theta_1 + L_3\sin\theta_2 = y_c \end{array} \right. \quad (1)$$

$$\begin{pmatrix} x_c \\ y_c \\ 1 \end{pmatrix} = \begin{pmatrix} \cos\theta_1 & -\sin\theta_1 & L_1(\cos\theta_1 - \cos\theta_2) \\ \sin\theta_1 & \cos\theta_1 & L_1(\sin\theta_1 - \sin\theta_2) \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} L_1 + L_3 \\ 0 \\ 1 \end{pmatrix} \quad (2)$$

$x_c = \boldsymbol{n}$, $y_c = \boldsymbol{h}$. θ_1, θ_2, ***h*** are variables.

Using data of angle between X-axis and two member bars measured by encoding disk in M1 and M2, the position of handle can be obtain. When the θ_1 and θ_2 are ascertained, the position of handle ***P*** can be obtained by equation 1. And because of $x_c = \boldsymbol{n}$ is a given value, $y_c = \boldsymbol{h}$ can be defined using only one variable. For example using θ_1, $y_c = \boldsymbol{h}$ are defined by:

$$y_c = h = L_1\sin\theta_1 + \sqrt{L_3^2 - n^2 + 2nL_1\cos\theta_1 - L_1^2\cos^2\theta_1} \quad (3)$$

In contrary, when the handle need to locate at a position, using the ***h***, θ_1 and θ_2 defined by:

$$\begin{array}{l} \theta_1 = \arctan\dfrac{a \pm \sqrt{a^2 + b^2 - c^2}}{b - c} \\ a = h, b = n, c = \dfrac{L_3^2 - (L_1^2 + n^2 + h^2)}{2L_1} \end{array} \quad (4)$$

$$\theta_2 = \arctan\frac{h - L_3\sin\theta_1}{n - L_1\cos\theta_1} \quad (5)$$

Using equation 4and 5, the position of handle can be controlled by transform the angle.

In order to develop the mechanism, the number of travel range of the handle should be obtained. Figure 5 shows extreme condition of system. When $\theta_1 = \theta_2$, the h will arrive the extremum.

$$\theta_1 = \theta_2 > 0, h_{max} = \sqrt{(L_1 + L_3)^2 - n^2}$$

$$\theta_1 = \theta_2 < 0, h_{min} = -\sqrt{(L_1 + L_3)^2 - n^2}$$

So the travel range of the handle is

$$h_{max} - h_{min} = 2\sqrt{(L_1 + L_3)^2 - n^2} \quad (6)$$

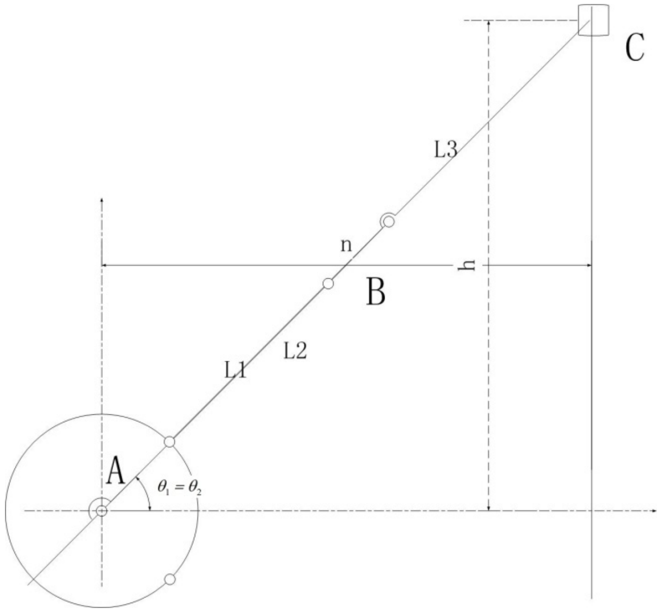

Figure 5 Extreme Condition of System

In the actual design, kinematics characteristics need to be considered. In any a position, the singular values of mechanism are defined by:

$$\sigma=\sqrt{\frac{L_1^2+L_3^2\pm\sqrt{(L_1^2-L_3^2)^2+4L_1^2L_3^2\cos^2(\theta_1-\theta_2)}}{2}} \tag{7}$$

The minimum and maximum of singular values, $\sigma_{\min}$ and $\sigma_{\max}$, respectively corresponding the equation the minus and plus. In any a position, $c=\sigma_{\min}/\sigma_{\max}$ is the condition number of mechanism, and $c \in [0, 1]$. When $\mathbf{c} \to 0$, kinematics characteristics of mechanism is poor. When $\mathbf{c} \to 1$, kinematics characteristics of mechanism is excellent. On the current mechanism with 2 degree of freedom, when $L_1 = L_3$, kinematics characteristics of mechanism is better. When $\theta_1=\theta_2$, mechanism takes singular configuration, workspace should avoid in $\theta_1=\theta_2$ neighbourhood. In order to ensure the linkages not cross, two joint angles should satisfy the conditions of $\theta_2 < \theta_1$. These constraints, $\theta_1 > \theta_2$. Therefore, theoretical maximal value travel range of the handle is impossible to reach. The number of travel range of the handle should smaller than $2\sqrt{(L_1+L_3)^2-N^2}$.

IV. EXAMPLE

According to the doctor's demand, the travel range of the handle should bigger than 200mm. Considering the influence of mechanical parts size and problem of singular values, number of travel range is defined as 300mm. In order to reduce size of mechanism, the n, the distance between the Y-axis and movement orbits of the handle, is defined as 200mm. Because the optimal characteristics of mechanism is at $L_1 = L_3$, length of two member bars are defined as ***l***.

According to the above equation, the number of l can obtain by:

$$h_{\max}-h_{\min}=2\sqrt{(L_1+L_3)^2-n^2} \tag{6}$$

$$h_{\max}-h_{\min}=300\text{mm}, n=200\text{mm}, L_1+L_3=2l.$$

$$\Rightarrow l=125mm$$

Hence, a set of design data which showed in figure 6 was obtained, number of travel range is 300mm, the distance between the Y axis and movement orbits of the handle is 200mm, length of each member bars are 125mm.

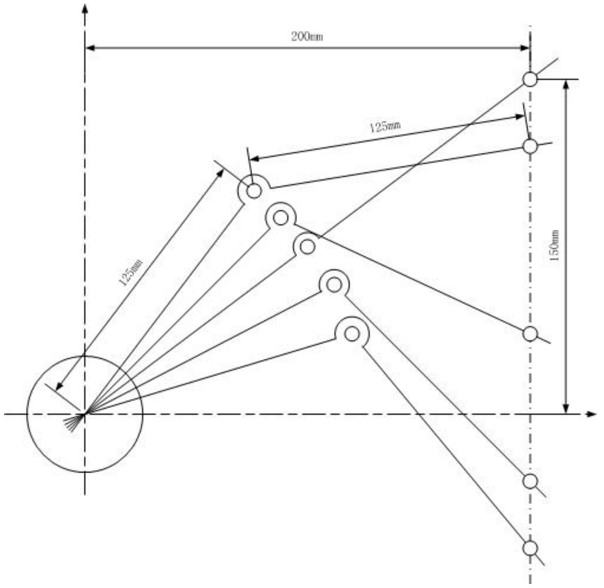

Figure 6 A set of design data

V. CONCULSION

A haptic controller for the catheter operation was proposed and the corresponding catheter manipulator was presented in the paper. The surgeon´s console simulates motions of surgeon´s hand to input control command and out force to the user. The corresponding catheter manipulator could follow the surgeon´s console with a same motion to insert a catheter into the blood vessel. A novel design of surgeon's controller was proposed. The surgeon's controller is suit for the developed catheter navigation system. According to the doctor's demand, it can choose distance between the motor and movement orbits of the handle, and size of travel range of the handle freely. In the future, this surgeon's controller and a catheter manipulator will constitute the complete a catheter navigation system.

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