Development of a Novel Robotic Catheter Manipulating System

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Abstract - Manual operation of steerable catheter is inaccurate in minimally invasive surgery and requires dexterity for efficient manipulation of the catheter simultaneously exposes the surgeons to intense radiation. In this paper, our objective is to develop a remote control system that replaces the manipulation of surgeons with high accuracy. Increasing demands for flexibility and fast reactions in control method, fuzzy control can play an important role because the experience of experts can be combined in the fuzzy control rules to be implemented in the systems. We present a practical application of fuzzy PID controller for this developed system during the remote operations and compare with the traditional PID control experimentally. The feasibility and effectiveness of the control method are demonstrated. The performance using the fuzzy PID control is much better than using the conventional control method.

Index Terms - Minimally Invasive Surgery, Robotic Catheter Manipulating System, Fuzzy PID Control, Remote Operation.

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 manipulating system could provide assistant to surgeons during the operation, but it has a long way to go to replace human being.

A lot of products and researches are reported in this area. One of the popular products is a robotic catheter placement system called Sensei Robotic Catheter System supplied by Hansen Medical [1]-[3]. 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. Catheter Robotics Inc. has developed a remote catheter system called Amigo [4]. This system has a robotic sheath to steer catheter which is controlled at a nearby work station, in a manner similar to the Sensei system. The first human trial of this system was in April 2010 in Leicester UK, where it was used to ablate atrial flutter. Magnatecs Inc. produced their Catheter Guidance Control and Imaging’ (CGCl) system [5]. This system has 4 large magnets placed around the table, with customised catheters containing magnets in the tip. The catheter is moved by the magnetic fields and is controlled at a nearby work station The Stereotaxis Niobe [6]. The system facilitates precise vector based navigation of magnetically enabled guide wires for percutaneous coronary intervention (a) Catheter manipulator (b) Controller Fig.1: Robotic catheter manipulation system (RCMS) by using two permanent magnets located on opposite sides of the patient table to produce a controllable magnetic field. Yogesh Thakur et al. [7] 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 [8]. 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 [9]-[14], [16], [22].
In this paper, a new prototype robotic catheter manipulating system has been designed and constructed based on the requirements for the endovascular surgery. Compared with robots mentioned above, our system features a slave manipulator that consists of one movement stage and one rotation stage, allowing for steering and inserting operation of the catheter simultaneously as Fig.1 (b) show. Also, the slave has a new developed force feedback measurement mechanism to monitor the proximal force which has been generated during the inserting catheter and provide the force feedback to the surgeon. The robotic catheter manipulating system has a master controller called surgeon console in Fig.1(a), uses the force sensor, torque sensor, dc, stepping motor encode and DSP to communicate the position and rotational angle to slave and, meanwhile provide the force feedback to the surgeon. The system was evaluated in aspect of performance of the rotation during remote operation in the master and slave part as Fig.1(c). Using fuzzy PID controller is to improve the adaptive ability of remote manipulations. Finally, radial performance of the system is demonstrated.

II. ROBOTIC CATHETER MANIPULATING SYSTEM

The RCMS is designed with the structure of master and slave. The surgeon console of the system is the master side and the catheter manipulator is the slave side. Moving mode of the catheter manipulator is designed as well as the surgeon console. The movable parts of surgeon console and catheter manipulator keep the same displacement, speed and rotational angles, therefore, the surgeon could operate the system smoothly and easily. Each of surgeon console and catheter manipulator side employs a DSP (TI, TMS320F28335) as their control unit. An internet based communication is built between the surgeon console and the catheter manipulator, the sketch map of the communication is shown in Fig.2. The console side sends axial displacement and rotational angle of the handle to the catheter manipulator. At the same time the catheter manipulator sends force information back to the console side. Serial communication is adopted between PC (HP Z400, Intel Xeon CUP 2.67GHz speed with 3GB RAM) and control unit of the mechanism. The baud rate of the serial is set to 19200 [15], [17], [18], [23].

A. The Catheter Manipulator

Fig.3 shows the catheter manipulator. This part is placed in the patient side. The catheter is inserted by using this mechanism. This part contains two DOFs, one is axial movement alone the frame, and the other one is rotational movement. Two graspers are placed at this part. The surgeon can drive the catheter to move along both axial and rotational motion when the catheter is clamped by grasper 1. The catheter keeps its position and the catheter driven part can move freely when the catheter is clamped by grasper 2. Inserting motion of the catheter is as shown in Fig.4. To realize axial movement, all catheter driven parts are placed and fixed on a movement stage (the green plate under motor 1 in Fig.3). The movement stage is driven by a screw which is driven by a stepping motor (motor 2 in Fig.3). On the other hand, a dc motor (motor 1 in Fig.3) is employed to realize the rotational movement of the catheter. The dc motor is coupled to the catheter frame by two pulleys which are coupled by a belt with teeth. The catheter is driven to rotating by motor 1 when the catheter is fixed on the frame by grasper1. Torque sensor is applied in this system to measure the torque information during the operation. The torque information will be sent to the controller side and generate a torque feedback to the surgeon. The torque sensor is linked to motor 1 and the axle of the pulley below. The resisting torque of the catheter can be transmitted to the torque sensor by coupled pulleys then measured by the torque sensor.
Resisting force acting on the catheter can be measured and will be sent to the controller and generated a haptic feedback to the surgeon. To measure the resisting force, a mechanism is designed as shown in Fig. 5 in detail. A loadcell which is fixed on the movement stage is employed to measure the resisting force. A clamp plate fixed on the loadcell is linked to the catheter frame which is supported by two bearings. The resisting force acting on the catheter in the axial direction can be detected by the loadcell when the catheter is fixed on the Fig. 5: Force measurement mechanism frame. The clamp plate doesn’t affect the rotating motion of the catheter frame [20], [21].

B. The Surgeon console

Fig. 6 shows the surgeon console of the RCMS. The surgeon console is the master side of the whole system and it is operated by the experienced surgeons. Surgeons carry out operations by using the console. A switch placed on the left handle is used to control these two graspers in catheter manipulator side; only one switch is enough because the catheter is clamped by one grasper at the same time. Surgeon’s action is detected by using the right handle. The movement part of catheter manipulator keeps the same motion with the right handle of the console. The right handle can measure two actions of the surgeon’s hand, one is axial movement and the other one is rotational movement. The handle is sustained by a bearing, and is linked to a loadcell; a pulley is fixed on the handle. An dc motor (Motor 1) with encoder is applied to generate torque feedback. A pulley which is couple to the upper one is fixed to the axle of the motor. All these parts are placed on a movement stage driven by a stepping motor (Motor 2).

Measurement of the axial movement is realized as following. A pulling/pushing force is measured by the loadcell when the surgeon pull or push the handle, according to this pulling force, the movement output displacement to keep the handle following the surgeon’s hand. Force feedback can be displaced by adjusting moving speed of the movement stage. The displacement and speed of the movement stage are sent to the catheter manipulator side, then the catheter manipulator keep synchronization with the surgeon console. When the surgeon rotates the handle, the rotation angle is measured by an encoder installed in the dc motor. The dc motor is working in the current control mode to generate the damping to the surgeon. The damping is calculated by the torque information from the catheter manipulator side.

The structure of the surgeon console is as well as the catheter manipulator; it means that the catheter manipulator could keep the same motions with the surgeon’s hand. The operation will become visualized and easy to begin. On the other hand, this structure can realize the mechanical feedback to the surgeon. The precision and accuracy of the system was evaluated by [17], the result was listed as Table I shown.

C. Control of the system

In the catheter manipulator side, each motor is couple with an encoder. Both rotation speed and rotation angle of these motors can be measured. So, the control algorithm should be designed to improve the precision and operating performance of the catheter manipulator during the remote manipulations. In the surgeon console side, the handle should

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<th>Precision</th>
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<td>Axial (mm)</td>
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<td>Radial (deg)</td>
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follow the surgeon’s hand. It means that, the output displacement/speed of stepping motor should be same or closed to input displacement/speed of surgeon’s hand. The movement speed and displacement of stepping motor can be measured by the encoder coupled to Motor 2 in Fig. 3, therefore, the dynamic models of system both axial and rotational motion need to be confirmed and the relationship between surgeon’s input force and displacement output of stepping motor can be built. As same as the relationship between input and output in the axial movement, the physical model of rotational movement also will be confirmed. In the catheter manipulator side, we use the fuzzy PID controller to improve the accuracy both displacement and rotation during the remote operations.

III. CONTROL STRATEGY OF THE SYSTEM IN ROTATION

A. Modeling of the rotational motion

Like most rotational systems, the rotational motion in consideration can be modelled as a mass system that the mass connected with flexible shaft or spring. The model can be simplified further as a mass connected by an inertia free flexible shaft, where the mass represents the total load that the motor rotates. A schematic diagram of the simplified rotational model is illustrated in Fig.7.

In modelling the dynamics of the simplified rotational movement, considering only linear dynamic or approximating the model as a linearized one is a common approach. However, the validity of the linear approximation and the sufficiency of the linearized dynamics in recovering the nonlinearities depend on the operating point and speed span of the rotational system.

For this case that the rotational motion [19] can be accurately modelled without considering the major nonlinear effects by the speed dependent friction, dead time and time delay, a linear model becomes to:

\[ m \ddot{\theta}(t) + c \dot{\theta}(t) = u(t) \]

Where \( u(t) \) is input torque, \( \theta(t) \) is the rotational angle, \( \dot{\theta}(t) \) is the velocity of rotational angle. Define \( \theta_1(t) = \theta(t) \), \( \theta_2(t) = \dot{\theta}(t) \) then

\[ \dot{\theta}_1(t) = A \Psi(t) + Bu(t) \]
\[ y(t) = C \Psi(t) \]

Where \( \Psi(t) = \begin{bmatrix} \theta_1(t) \\ \theta_2(t) \end{bmatrix} \), \( A = \begin{bmatrix} 0 & 1 \\ 0 & -\frac{c}{m} \end{bmatrix} \), \( B = \begin{bmatrix} 0 \\ 1 \end{bmatrix} \), \( C = \begin{bmatrix} 1 & 0 \end{bmatrix} \), \( m \) is quality of the handle, \( c \) is the viscous damping coefficient.

Parameters of the dynamic model are shown as following: \( m = 0.5kg, c = 0.02N/(m/s), k = 1N/m \).

B. Controller design in rotational motion

A PID controller used in the RCMS is easily designed with good performance during the remote control, however, when different condition of operation effects are concerned, a PID controller should be turn or redesign to maintain desirable responses. We redesign a fuzzy PID controller to provide a better control command to improve the performance of the system. The basic fuzzy PID configuration is shown in Fig.8.

For the design of fuzzy PID controller, first, the fuzzification stage should convert a crisp number into the fuzzy values within a universe of discourse \( U \). The \( U \) is quantified and normalized to \([-1, +1]\). Then, we utilize the triangle-shaped membership function with seven term sets. They are NB (negative big), NM (negative medium), NS (negative small), ZR (zero), PS (positive small), PM (positive medium), PB (positive big). We construct the rule base according to control engineering knowledge, and the scaling factors are set to be 1.

Each combination of error fuzzy set and error change fuzzy set need a control action. Forty-nine control rules are developed and presented. The Mamdani type controller is preferred because an extremely short time is required for its development and ease with which its functions can be understood. The defuzzification method based on the centre of gravity that is commonly used in applications of fuzzy control. The key issue in such control problem is to hold a variable to constant set point. As the design objective, the overshoot in displacement and angle are desired to be not bigger than 5% for nominal value. The set of fuzzy rules has been based on fast attaining of the desired one and avoided its overshoots.
Fig. 9 describes the experimental setup for the rotational motions using PID controller.

IV. EXPERIMENTAL RESULTS

Firstly, we perform a basic experiment during the remote control operations with PID controller. In this case, the characteristics of the performance can be obtained experimentally. Then, we go ahead to use the designed fuzzy PID controller to improve the accuracy of remote operations. The values of conventional PID control parameters are determined, and coefficients are denoted to be: 

\[ k_p = 7.3, k_i = 5, k_d = 4.1 \] 

The experimental results are described as Fig. 10 and Fig. 11.

For modeling the DC motor, we used the physical approach to build the dynamic model of rotational motion, but we should consider that operate at varying conditions or require high precision operation raise the need for a nonlinear approach in modeling and identification. Most of mechanical systems used in industry are composed of masses moving under the action of position and velocity dependent forces. These forces exhibit nonlinear behaviour in certain regions of operation. For a system having two DOFs (rotation and insertion), the nonlinearities significantly influence the system operation when the velocity and rotation change the direction. So, we should focus on the nonlinear modelling of system dynamic and parameters identification in the future.

V. CONCLUSIONS

In this paper, a novel robotic catheter manipulating system (RCMS) was proposed. We developed a high precision mechanical system to assist surgeon completing the surgery procedures in the operation. In this system, we used DSP which has highly precision and processing speed as control unit in the master and slave side. The loadcell and torque sensor were utilized to measure the value of force and rotation torque. We designed a novel force feedback mechanical structure to measure the proximal force, meanwhile the surgeon could feel the force feedback to avoid damages happened in the operation. Secondly, we designed the fuzzy PID controller which is used in the manipulator side. The presented fuzzy PID controller had better performance in the rotational movement. Although, there also has few errors, it can satisfy the practical application in minimally invasive surgery. Experimental results confirm the fact that the fuzzy control method is suitable to be used and it is easy to be understood.

In future work, we will reconsider the dynamic model of the system in the aspect of nonlinear.

References


