Development of a Novel Robotic Catheter Manipulating System with Fuzzy PID Control

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ABSTRACT

Manual operation of steerable catheter is inaccurate in minimally invasive surgery, requiring dexterity for efficient manipulation of the catheter, and it exposes the surgeons to intense radiation. The authors' objectives are to develop a robotic catheter manipulating system that replaces the surgeons with high accuracy. Increasing demands for flexibility and fast reactions in a control method, fuzzy control (FC) can play an important role because the experience of experts can be combined in the fuzzy control rules to be implemented in the systems. They present a practical application of a fuzzy PID control to this developed system during the remote operations and compare with the traditional PID (Proportional-Integral-Derivative Controllers) control experimentally. The feasibility and effectiveness of the control method are demonstrated. The synchronous manipulation performance with the fuzzy PID control is much better than using the conventional PID control method during the remote operations.

Keywords: *Fuzzy Proportional-Integral-Derivative Controllers (PID) Control, Manipulation Performance, Minimally Invasive Surgery (MIS), Remote Operation, Robotic Catheter Manipulating System (RCMS)*

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.

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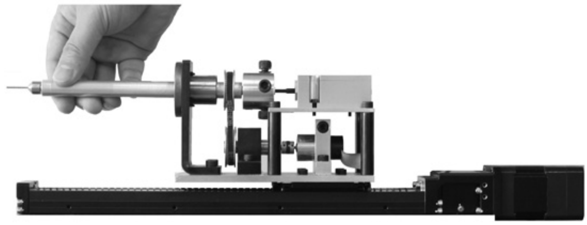
In the operation, for example the catheter is inserted through patients' blood vessel. Any mistakes would hurt patients and cause damages. An experienced neurosurgery doctor can achieve a precision about 2mm in the surgery. However, the contact force between the blood vessel and the catheter cannot be 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 (Amin, Grossman, & Wang, 2005; Pappone, Vicedomini, & Manguso, 2006; Srimath, Kesavadas, & Li, 2010). 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 (Knight, Ayers, & Cohen, 2008). 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 trail 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 (CGCI) system (Nguyen, Merino, & Gang, 2010). 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 Inc. developed a magnetic navigation system: the Stereotaxis Niobe (Ernst & Ouyang, 2005). The system facilitates precise vector based navigation of magnetically enabled guide wires for percutaneous coronary intervention Catheter manipulator Controller Figure 1 and Figure 2: Remote Catheter Navigation System (RCNS) by using two permanent magnets located on opposite sides of the patient table to produce a controllable magnetic field. Yogesh Thakur et al. (2009) 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. Fukuda et al. (Arai, Fujimura, Fukuda, & Negoro, 2002) 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 (Fu, Gao, Liu, & Guo, 2010; Ikeda, Arai, Fukuda, Kim, Negoro, Irie, & Takahashi, 2005; Koa, Kanagaratna, Wallace et al., 2007; Nainggolan, 2008; Peirs, Clijnen, Reynaerts, Brussel et al., 2004; Saliba, Reddy, Wazni et al., 2008; Wang, Zhang, & Liu, 2010).

In this study, a new prototype robotic catheter manipulating system has been designed and constructed based on the requirements for the endovascular surgery. Compared with robots

Figure 1. Robotic catheter manipulating system. Surgeon console.



mentioned above, our system features a slave navigator that consists of one movement stage and one rotation stage, allowing for steering and inserting operation of the catheter simultaneously as Figure 2 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 RCMS has a master controller called surgeon console in Figure 1, uses the force sensor, torque sensor, dc, stepping motor encode and DSP to communicate the position and rotational angle to slave, meanwhile provide the force feedback to the surgeon. The system was evaluated in aspect of performance by the measurement of position and rotation between master and slave. Using fuzzy PID controller is to improve the accuracy of the remote manipulations. Finally, the synchronous manipulation performance of system is demonstrated in displacement accuracy of axial and rotational movement.

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 navigator is the slave side. Moving mode of the catheter navigator is designed as well as the surgeon console. The movable parts of surgeon console and catheter navigator keep the same displacement, speed and rotational angles, therefore, the surgeon could operate the system smoothly and easily. Each of surgeon

Figure 2. Robotic catheter manipulating system. Catheter navigator.

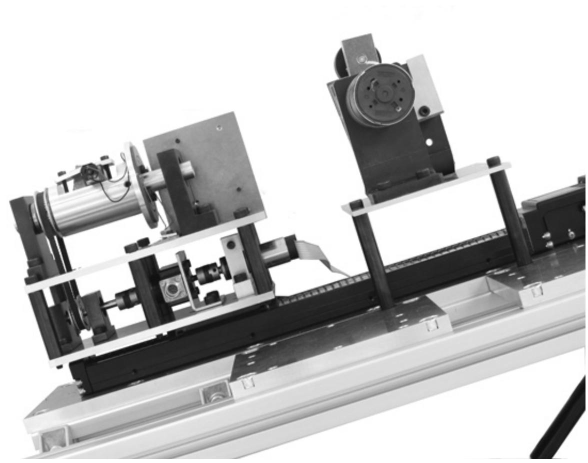
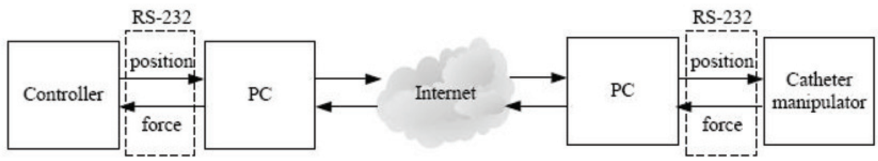


Figure 3. Communication sketch map



console and catheter navigator employs a DSP (TI, TMS320F28335) as their control unit. An internet based communication is built between the surgeon console and the catheter navigator, the sketch map of the communication is shown in Figure 3. The console side sends axial displacement and rotational angle of the handle to the catheter navigator. At the same time the catheter navigator 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 (Guo, Guo, Xiao, Ma, Yoshida, Tamiya, & Kawanishi, in press; Xiao, 2011).

The Catheter Navigator

Figure 4 shows the catheter navigator. 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 Figure 5.

To realize axial movement, all catheter driven parts are placed and fixed on a movement stage (the green plate under motor 1 in Figure 4). The movement stage is driven by a screw which is driven by a stepping motor (motor 2 in Figure 4). On the other hand, a dc motor (motor 1 in Figure 4) 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.

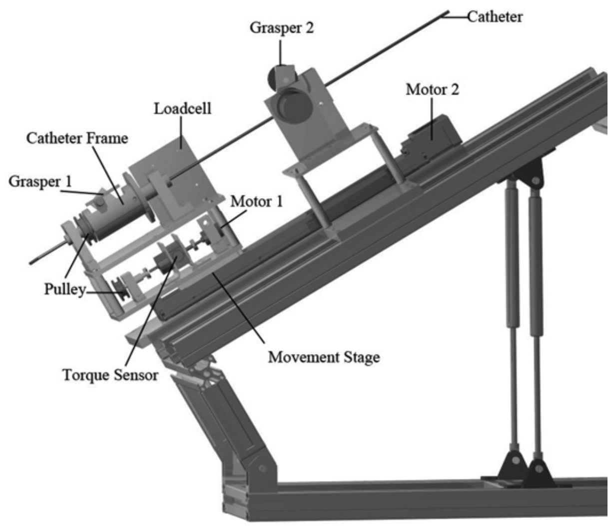
Torque sensor is applied in this system to measure the torque information during the operation. The torque information will be sent to the console side and generate a torque feedback to the surgeon. The torque sensor is linked to motor 1 and the axle of the pulley below. The resisting torque of the catheter 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 Figure 6 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 Figure 6: Force measurement mechanism frame. The clamp plate doesn’t affect the rotating motion of the catheter frame (Ma, Guo, Xiao et al, 2011; Xiao, 2011).

The Surgeon Console

Figure 7 shows the surgeon console of the RCMS. The surgeon console is the master side of the whole system and it is operated by the

Figure 4. Catheter navigator



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 navigator 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 navigator keeps the same motions 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. A 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

Figure 5. Inserting motions

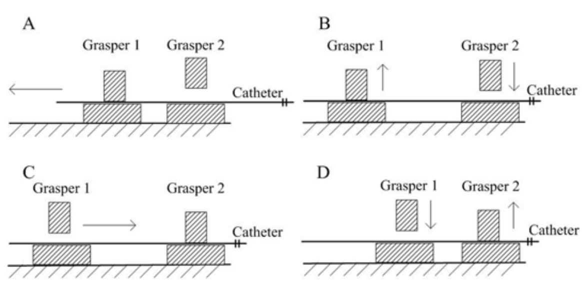
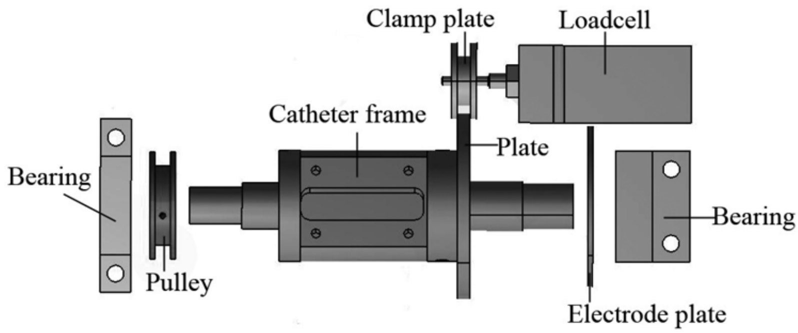


Figure 6. Force measurement mechanism



are sent to the catheter navigator side, then the catheter navigator 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 navigator side.

The structure of the surgeon console is as well as the catheter navigator; it means that the catheter navigator 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 Xiao (2011), the result was listed in Table 1.

Control of the System

In the catheter navigator 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 navigator during the remote manipulations. In the surgeon console side, the handle should 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 Figure 4, therefore, the dynamic models of system both axial and rotational motion need to be confirmed and the

Figure 7. Structure of the surgeon console

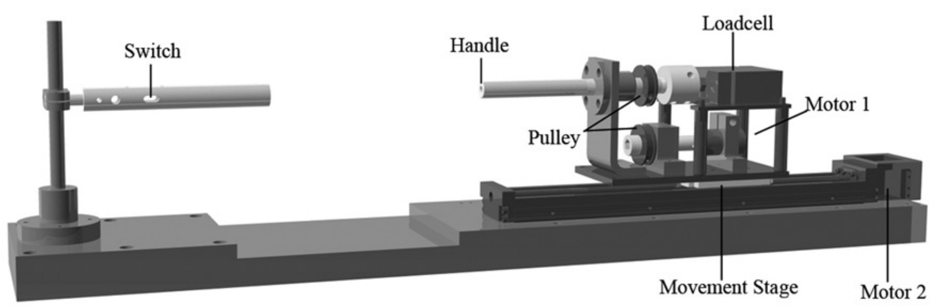


Table 1. Evaluation of the precision

Surgeon Console		Precision	Accuracy
	Axial (unit: mm)	0.35	0.025
	Radial (unit: deg)	3.1	2.1
Catheter Navigator			
	Axial (unit: mm)	0.23	0.04
	Radial (unit: deg)	2.2	3.0

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 navigator side, we use the fuzzy PID controller to improve the accuracy both of displacement and rotation during the remote operations.

FUZZY CONTROL

Traditional control design methods use mathematical models of a system and its inputs to design controllers that analyse their effectiveness. FC uses fuzzy sets and fuzzy inference to derive control laws in which no precise model of the system exist, and most of the a priori information is available only in qualitative form. The basic idea of FC is to make use of expert knowledge and experience to build a rule base with linguistic rules (Mamdani, 1974). A fuzzy rule is a conditional statement, expressed in the form IF Then. There are two difficulties in designing any fuzzy logic control system: (1) the shape of the membership functions and (2) the choice of the fuzzy rules (Kuo & Lin, 2002).

The proposed FC system is shown in Figure 8 and the fuzzy controller operation, in general, is typically divided into the following three categories: fuzzification, inference engine and defuzzification. The fuzzification block means that real world variables are translated in terms of fuzzy sets. In a fuzzy inference engine, the control actions are encoded by means of fuzzy inference rules. The results of the fuzzy computations are translated in terms of real values for the fuzzy control action in the defuzzification block.

Input Variables and Normalization

The first step in FC is to take physical values of the system variables from the A/D converter and map them into a normalized domain. A fuzzy logic (FL) controller usually uses the error (e(k)) and the change of error (ce(k)) as the input variables.

$$e(k) = y_r(k) - y_m(k) \tag{1}$$

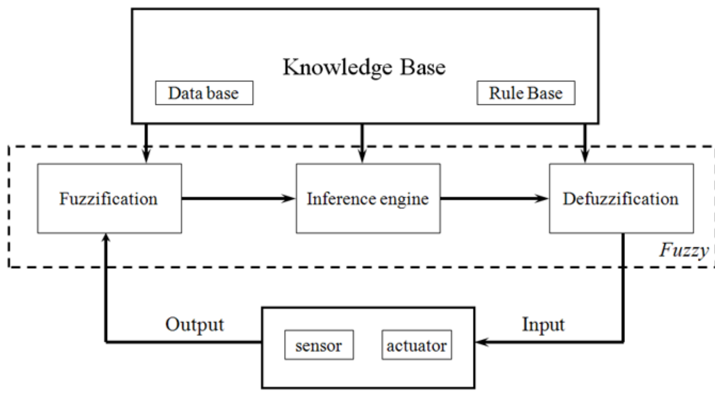
$$ce(k) = \frac{e(k) - e(k-1)}{T} \tag{2}$$

Where $y_r(k)$ and $y_m(k)$ are the reference and output, respectively, T is the sampling period, and $e \in [-l_e, l_e]$, $ce \in [-l_d, l_d]$, T, l_e, $l_d \in R^+$, R^+ denotes the set of all positive real values. To obtain the FC inputs, a reference value $y_r(k)$ has to be determined, and the system output $y_m(k)$ should be obtained from a sensor. Normalization of the $e(k)$ inputs and $ce(k)$ requires a scale transformation that maps the physical values of the system variables into a normalized domain as:

$$e_N(k) = k_e e(k) \tag{3}$$

$$ce_N(k) = k_d ce(k) \tag{4}$$

Figure 8. General structure of fuzzy control



Where k_e and k_d are the input scaling factors, $e_N, ce_N \in [-L, L]$, and $k_e, k_d, L \in R^+$.

Fuzzification and Membership Functions

The membership functions used in the fuzzification play a crucial role in the final performance of a fuzzy control system, and the choice of the membership function has a strong influence on the control effect (Bagis, 2003; Sun & Liu, 2002). There are several types of membership functions used in FC such as the triangular function, bell function, Gaussian function and trapezoidal function (D'Errico, 2001; Liang, Yeap, Hermansyah, & Rahmati, 2003). The triangular type membership function is most commonly used in FC applications because of its computational efficiency and simplicity (Liang, Yeap, Hermansyah, & Rahmati, 2003).

Rule Base

While the differential equations are the language of conventional control, IF-THEN rules about how to control the system are the language of fuzzy control, since an IF-THEN operator is the simplest and most widely used interpretation and, it provides computational efficiency (D'Errico, 2001). The control engineering knowledge method based on IF-THEN rules is the commonly used method to construct the rule base, since it needs more engineering skills and experience than plant information. Generally, the rules for the present problem are structured as:

r_i: IF e_N is A_i and ce_N is B_i THEN u_{fz} is C_{ij}

Where r_i denotes the fuzzy rules; $i = 1, 2, \ldots\ldots, n$, n is the number of fuzzy rules; A_i and B_i denote input linguistic values from the fuzzy sets of the antecedent part of the controller for the e_N and ce_N, respectively, C_{ij} denotes the output linguistic values from the fuzzy set of the consequent part of the controller for the u_{fz}.

Inference Engine

An inference engine is an interface that produces a new fuzzy set. The inference method for fuzzy control can be categorized into two groups: the direct inferencing and indirect inferencing (Yan, Ryan, & Power, 1994). Control values are determined on the basis of the inferred state. It has been noted that indirect inference employs a small number of production rules, and this method is regarded as the Sugeno-Tagaki method. The direct method is commonly used in applications of FC because of the simplicity of using the min (T-norm) -max (T-conorm) operator. This operation is called Mamdani type inference, which is recommended for use because it produces stronger control action in some certain cases. To perform this method, first, the degree of match between the meaning of the crisp inputs and the fuzzy sets describing the meaning of the rule antecedent should be computed for each rule by using the min operator (T-norm approach).

$$\mu_{C_{ij}}(e_N, ce_N) = \min\{\mu_{A_i}(e_N), \mu_{B_i}(ce_N)\} \tag{5}$$

Where $\mu_{C_{ij}}(e_N, ce_N) \in [0,1]$, and then, the max (T-conorm) operator is performed as:

$$\mu_{con}(u_{fz}) = \max\{\mu_{C_{ij}}(u_{fz})\} \in R \tag{6}$$

Where μ_{con} denotes the meaning of the rule consequent part, $\mu_{C_{ij}}(u_{fz})$ denotes the value for the control output of the related rule.

Defuzzification

Defuzzification is the procedure that produces a real value from the result of the inference, which could be used as a fuzzy control input. The most widely used defuzzification method is the centre of gravity method, which extracts the value corresponding to the centre of gravity of the fuzzy set describing the involving signal (Bagis, 2003), and it is computationally efficient (Kuo & Lin, 2002). On the other hand, the Sugeno-Tagaki's defuzzification method is a kind of experimental design method. It is time consuming and not practical. According to the centre of gravity method, the crisp value of the fuzzy control output is given by

$$u_{fz} = \frac{\sum_{i=1}^{n_{rules}} \{membership(input_i) \times output_i\}}{\sum_{i=1}^{n_{rules}} \{membership(input_i)\}} \tag{7}$$

Where i is the rule number.

Output Normalization

The rules, along with the membership degree of the fuzzy inputs with the fuzzy inference engine, determine the fuzzy output u_{fz} in the defuzzification. This output should be denormalized by using a scaling factor to obtain the real control input $u_f(k)$.

$$u_f(k) = k_u u_{fz}(k) \tag{8}$$

Where $u_{fz}(k) \in [-l_{fz}, l_{fz}]$, $u_f \in [-H, H]$ and $k_u, l_{fz}, H \in R^+$.

A diagram of the conventional FC is illustrated in Figure 9. The appropriate selection of input and output scaling factors (k_e, k_d, k_u) is very important because they have significant effects on the stability and performance of the systems.

PID Fuzzy Control

Conventional FC may result in steady state errors if the system does not have an inherent integrating property. To improve conventional FC, some algorithms have been proposed in the literature such as Fuzzy PID control. The PID type of FC is known to be more practical and generates incremental control output via integral action at the output. As the structural difference, the rule base of the PID-FC is different from that of the conventional FC in order to reduce overshoot and settling time. The structure of a PID type FC is shown in Figure 10. The PID type of FC is capable of reducing steady state error, and it is known to give good performance in transient responses. Where k_i is the positive constant for the integral gain. PI-FLC has been developed to improve the transient response and Figure 11 shows the PI-FC diagram.

Figure 9. Conventional FC diagram

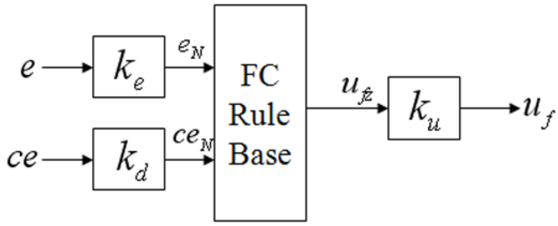
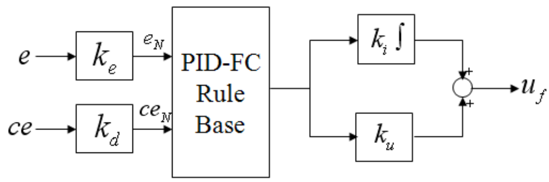


Figure 10. Fuzzy PID control diagram for PID-FC



MODELING OF THE RCMS DYNAMICS

Dynamic Model of the Axial Motion

Accurate model building is a crucial stage in practical control problems. An adequately developed system model is essential for reliability of the designed control. Consequently, the system modelling process is vital for control and identification problems. In modelling the axial motion, the aim is to find the governing equations that express the input pulling force and relate the stepping motor output displacement. A schematic diagram of axial motion built (Ma, 2011) with regard to the aim expressed below is given in Figure 12. The diagram shows the relationship between surgeon's input force and resistance. The equation that describes the physical relationship by using Newton's second law is as follows:

$$F(t) = \mathrm{m}\ddot{x} + c\dot{x}(t) + kx(t) \quad (9)$$

Where $F(t)$ is the pulling force, $x(t)$ is the moving displacement, $\dot{x}(t)$ is the velocity of hand movement. Define $x_1(t) = x(t)$, $x_2(t) = \dot{x}(t)$ then

$$\begin{aligned} \dot{x}(t) &= AX(t) + Bu(t) \\ y(t) &= CX(t) \end{aligned} \quad (10)$$

Where $X(t) = \begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix}$, $A = \begin{bmatrix} 0 & 1 \\ -\dfrac{k}{m} & -\dfrac{c}{m} \end{bmatrix}$, $B = \begin{bmatrix} 0 \\ \dfrac{1}{m} \end{bmatrix}$, $C = \begin{bmatrix} 1 & 0 \end{bmatrix}$, m is quality of the

Figure 11. Fuzzy PID control diagram for PI-FC

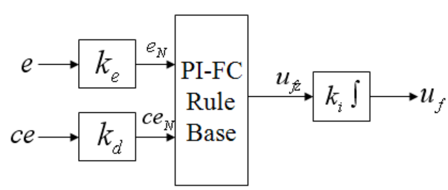
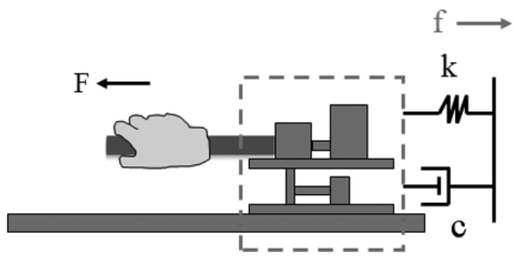


Figure 12. Diagram of axial dynamic model



handle, c is the viscous damping coefficient, k is the coefficient of elasticity.

Dynamic Model 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 Figure 13.

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 (Guo, 2011) can be accurately modelled without considering the major nonlinear effects by the speed dependent friction, dead time and time delay, a linear model becomes

$$m\ddot{\theta}(t) + c\dot{\theta}(t) = u(t) \tag{11}$$

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

$$\begin{aligned} \dot{\theta}(t) &= A\Psi(t) + Bu(t) \\ y(t) &= C\Psi(t) \end{aligned} \tag{12}$$

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

Parameters of the dynamic model are shown as following:

Figure 13. Diagram of rotational dynamic model

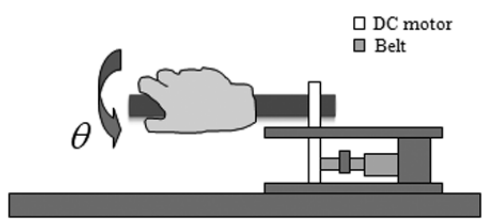
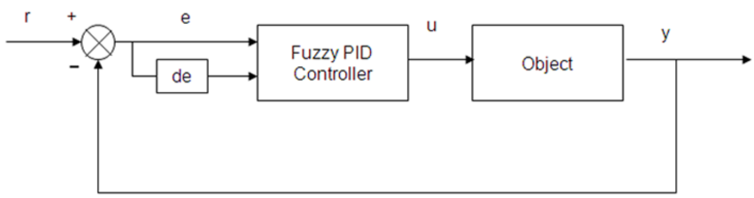


Figure 14. Principle diagram of fuzzy PID control



$m = 0.5kg, c = 0.02N / (m / s), k = 1N / m$
.

Fuzzy PID Controller Design of the RCMS

The PID control is the most widely used controller in industry today, and it possesses the simple, robust, and stable properties. The analog version of a PID control is

$$u(t) = k_p e(t) + k_i \int_0^t e(t)dt + k_d \frac{de(t)}{dt} \tag{13}$$

Where $e(t) = r(t) - y(t)$ and $u(t)$ is the PID controller output. The control signal is thus a sum of three terms: the P-term (which is proportional to the error), the I-term (which is proportional to the integral of the error), and the D-term (which is proportional to the derivative of the error). The controller parameters are proportional gain k_p, integral gain k_i, derivative gain k_d. The integral, proportional and derivative part can also be interpreted as control actions.

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 design a fuzzy PID controller to provide a better control command to improve the performance of the system during remote control operations. The basic fuzzy PID configuration is shown in Figure 14.

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 as shown in Figure 15 and Figure 16 through Figure 18. 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 3% for nominal value. The set of fuzzy rules has been based on fast attaining of the desired one and avoiding its overshoots.

EXPERIMENT

Experimental Setup

Experiments are conducted by using the RCMS that consists of master (surgeon console) and slave (catheter navigator) connected via inter-

Figure 15. Membership function for the $e(k)$ *and* $ce(k)$

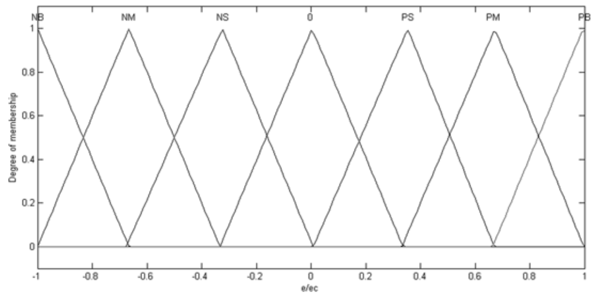
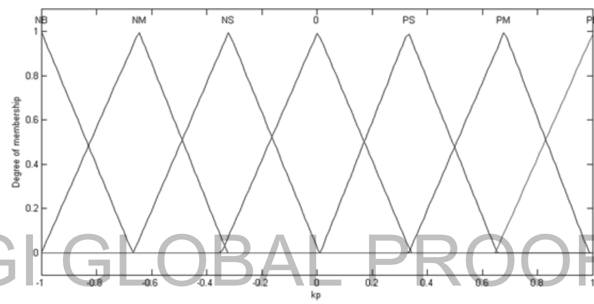


Figure 16. (a) Membership function for the k_p



net. The stepping motor and dc motor which are employed to drive the catheter moved in axial and rotational direction. Consequently, examination of stepping motor and dc motor behaviours during the remote operations constitute a useful effort for analysis and control of many practical applications. The control diagram of the experimental setup is shown in Figure 19 and the system is interfaced with the fuzzy PID controller as a two inputs and one output structure. The displacement error ($e(k)$) and change of displacement error ($ce(k)$) are used as the inputs to the FC, since it has been shown that using the error and its derivative as

Figure 17. (b) Membership function for the k_i

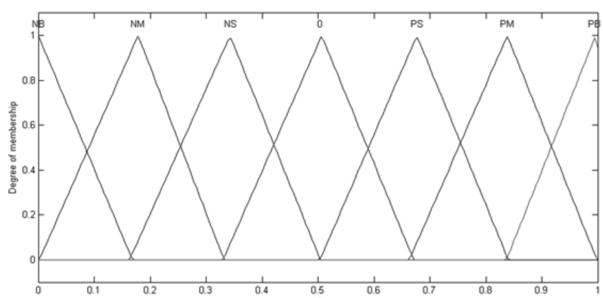
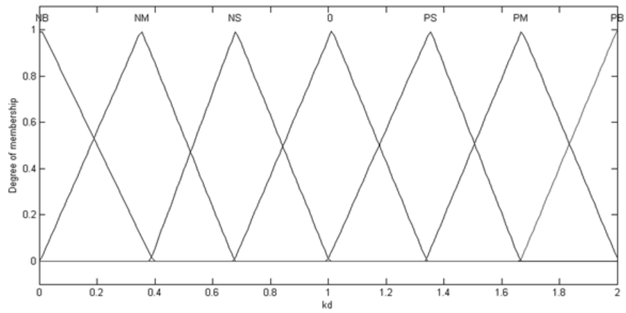


Figure 18. (c) Membership function for the k_d



inputs to FC leads to stable control in a large of control problems. The FC generates the primary command for the catheter navigator side of RCMS and adjusts axial and rotational status that uses to maintain good steady state and transient behaviour. The measured output by encode is transferred to the DSP (TI, TMS320F28335). The implementation of the FC is performed using the following procedures: measure the current output of displacement in stepping motor or angle in dc motor; calculate the error and error change; fuzzify the inputs using the rule base, otherwise the membership functions with IF-THEN operation; transform the fuzzified inputs into fuzzy inference using min-max operation; finally, defuzzify the information using the centre of gravity method to convert to fuzzy control. Then the defuzzified information consisted of k_p, k_i, k_d is transmitted to the PID controller and used as the input control signals to adjust the output signal $u(t)$.

Experimental Results

First, 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 experimental results obtained from axial displacement with PID are shown in Figure 20 and the force input signal is described in Figure 21. A smooth response is obtained without overshoot by using the fuzzy PID controller shown in Figure 22 and the force input signal is demonstrated by Figure 23. The values of conventional PID control parameters are determined, and coefficients are denoted to be: in term of axial movement as following: $k_p = 10.8, k_i = 8.2, k_d = 1.5$; in term of rotational movement as following: $k_p = 7.3, k_i = 5, k_d = 4.1$.

The PID controller had many steady-state errors, and performance of tracking was much worse than the fuzzy PID controller. However, the conventional fuzzy PID performed well, but it has a few errors, these because of the time delay of remote operations. The input signal is the pulling force, we used the mathematic equation to calculate out values of axial displacement then used DSP control unit to translate the values as input signals for stepping motor.

The tracking performance of rotation with the fuzzy PID controller showing in Figure 25 was much better than that with PID showing in Figure 24, not only for the steady-state error and overshoot, but also for the shortest rise time and precision. It can provide much better tracking performance. Based on the experimental results, it can be concluded that the overshoot was significantly reduced to the desired level, and axial displacement and rotational angle were improved such that tracking speed and accuracy of behaviour tracking were obviously improved compared to these with PID controller.

Figure 19. Diagram of the experimental setup for the fuzzy PID controller

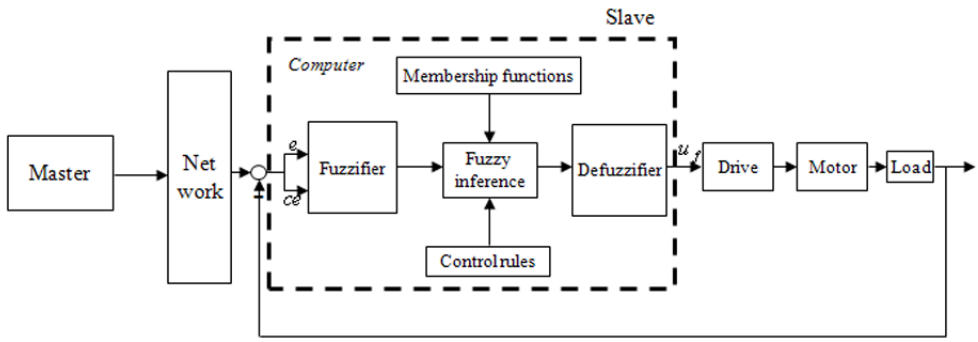


Figure 20. Axial tracking curve with PID

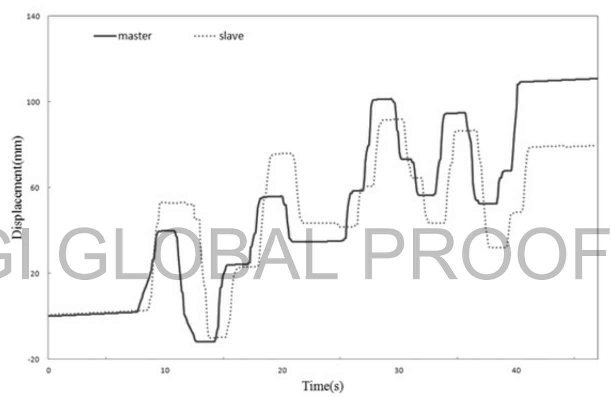


Figure 21. Input force signal

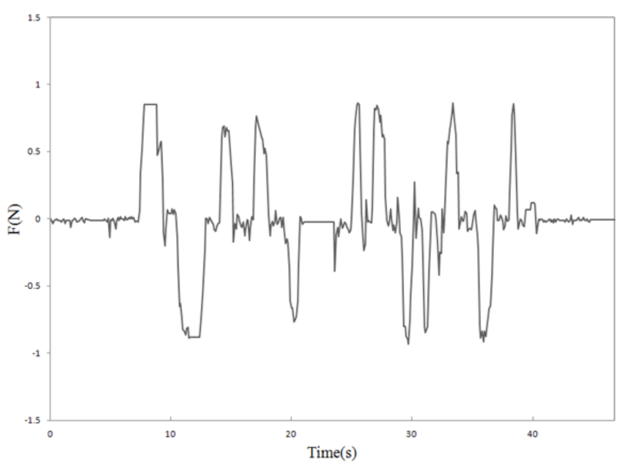


Figure 22. Axial tracking curve with fuzzy PID

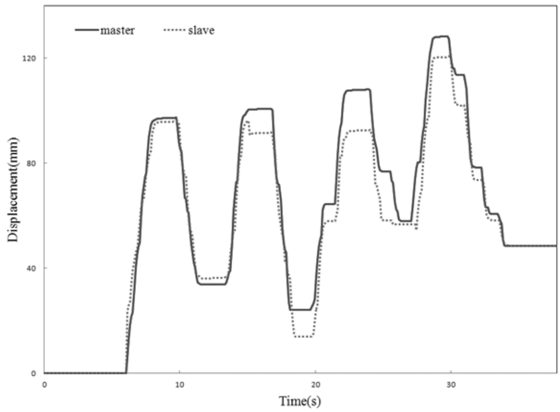


Figure 23. Input force signal

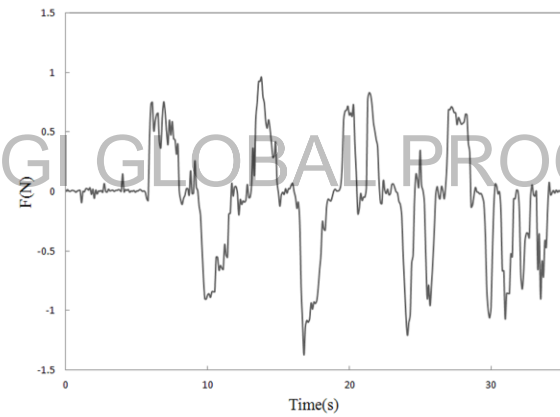


Figure 24. Rotation tracking curve with PID

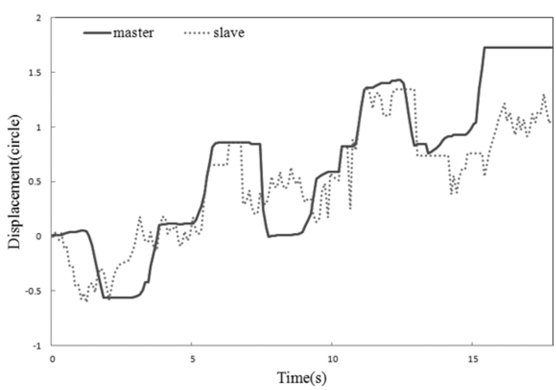
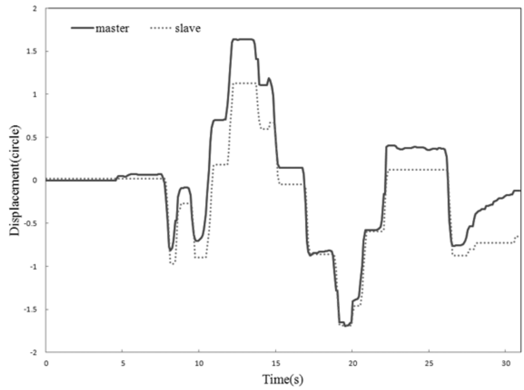


Figure 25. Rotation tracking curve with fuzzy PID



However, for modelling the dc motor, we used the physical method 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 modelling 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.

CONCLUSION AND FUTURE WORK

In this paper, a novel robotic catheter manipulating system (RCMS) was proposed. We developed a high precision mechanical system with remote control to assist surgeon to complete the operational procedures in intravascular neurosurgery operation. In this system, we used DSP as control unit both in surgeon console and catheter navigator which has highly precision and processing speed. The loadcell and torque sensor were utilized to get information of force and rotation torque. We designed a novel force feedback mechanical structure to measure the proximal force and the surgeon could feel the force feedback to avoid damages during the operation. Secondly, we designed the fuzzy PID controller that is used in the catheter navigator side, the accuracy of axial and rotational movement during the remote operations have been improved and comparing with the conventional PID control method, the presented fuzzy PID controller is much better quality of response during insertion and rotation. The tracking error with fuzzy PID is below 3mm and 10° during the remote control. Although there also has a little error in the rotational and axial movement because of time delay, it also can satisfy the application of practical application in minimally invasive surgery. Experimental results confirm the fact that the fuzzy logic control method is suitable to be used and it is easy to understand and employ the system dynamic model freely. Finally, it should be said that the fuzzy PID control algorithm is the alternative approach to be used as the system control method. Also, we should know that two of the most important information is force (contact and friction) and displacement of the catheter inside the vascular.

In future work, we will rebuild the dynamic model of the robotic catheter manipulating system in rotational movement to improve the precision and do the remote operations with catheter into the endovascular. The force (contact force and friction force) and displacement information should be got by the fiber sensor/force feedback mechanism and magnetic sensor.

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