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NARX Model-based Identification for the Developed Novel Robotic Catheter Manipulating System

Xu Ma*[1], Shuxiang Guo[2,4], Nan Xiao[2], Jin Guo[1], Shunichi Yoshida[2],
Takashi Tamiya[3] and Masahiko Kawanishi[3], Baofeng Gao[2]

[1] *Graduate School of Engineering, Kagawa University, Takamatsu, Kagawa, Japan*
2217-20, Hayashi-cho, Takamatsu, 761-0396 Kagawa, Japan
[2] *Intelligent Mechanical Systems Engineering Department, Kagawa University, Takamatsu, Kagawa, Japan*
[3] *Department of Neurological Surgery, Faculty of Medicine, Kagawa University, Takamatsu, Kagawa, Japan*
[4] *Harbin Engineering University, Harbin, Heilongjiang Province, China*
s10d641@stmail.eng.kagawa-u.ac.jp；guo@eng.kagawa-u.ac.jp;

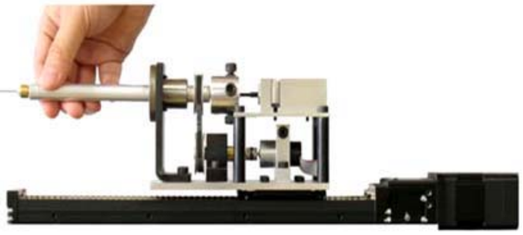
***Abstract* - Manual operation of steerable catheter is inaccurate in minimally invasive surgery and requires dexterity for efficient manipulation of the catheter meanwhile exposes surgeons to intense radiation. In this paper, our objective is to develop a remote control system that replaces the manipulation of surgeons with high accuracy and precision. The system identification for nonlinear discrete time is presented by NARX (Nonlinear ARX) method. Input force signal and output displacement signal have been measured experimentally as the reference item to identify the system dynamic equation by using Matlab toolbox. After analyzed and compared with 3 kinds of typical system mathematical model, the dynamic characteristic of system was shown that the system could be locally described in terms of a suitable NARX model and it guarantees local stability and robust.**

Index Terms - Minimally Invasive Surgery, Robotic Catheter Manipulating System, Nonlinear System, NARX Model, System Identification.

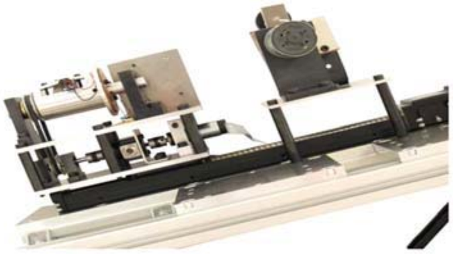
I. INTRODUCTION

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 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 [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 Inc. developed a magnetic navigation system: 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]-[11], [13], [16]



(a) The surgeon console



(b) The catheter manipulator

Fig.1 The robotic catheter manipulating system

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 identification has been done by the Matlab tool box of system identification. Finally, the comparison results have been shown and the proposed nonlinear ARX model has the smallest difference with measured values than the other models.

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. [12], [14], [15]

Fig.2 The communication sketch map

A. *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 [17], [18].

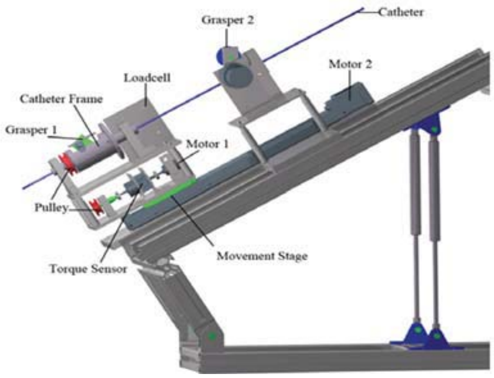


Fig.3 The catheter manipulator

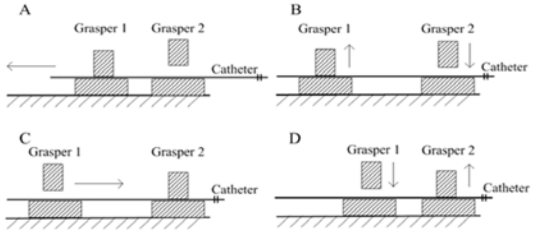


Fig.4 The inserting motions

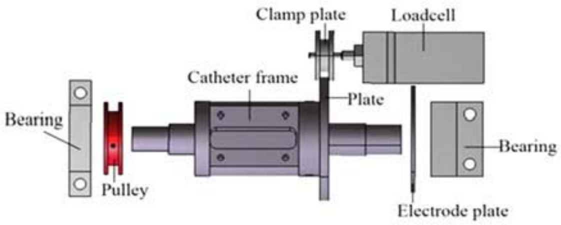


Fig.5 The force measurement mechanism

B. *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. 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 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.

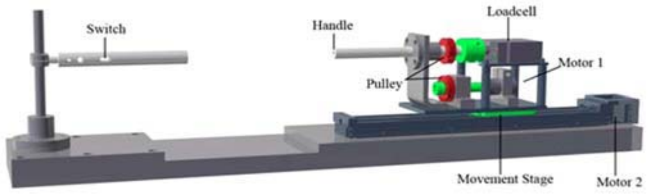


Fig.6 Structure of the surgeon console

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.

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 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. NONLINEAR ARX SYSTEM IDENTIFICATION

A. Definition of Nonlinear ARX Model

A nonlinear ARX model can be understood as an extension of a linear model. A linear SISO ARX model has this structure:

$$\begin{aligned} &y(t)+a_1y(t-1)+a_2y(t-2)+\ldots+a_{na}y(t-na)= \\ &b_1u(t)+b_2u(t-2)+\ldots+b_{nb}u(t-nb+1)+e(t) \end{aligned} \tag{1}$$

This structure implies that the current output $y(t)$ is predicted as a weighted sum of past output values and current and past input values. Rewriting the equation as a product:

$$\begin{aligned} &y_p(t)=[-a_1,-a_2,\ldots,-a_{na},b_1,b_2,\ldots,b_{nb}]* \\ &[y(t-1),y(t-2),\ldots,y(t-na),u(t),u(t-1),\ldots,u(t-nb-1)]^T \end{aligned} \tag{2}$$

Where $y(t-1),y(t-2),\ldots,y(t-na),u(t),u(t-1),\ldots,u(t-nb-1)$ are delayed input and output variables, called regressors. The linear ARX model thus predicts the current output y_p as a weighted sum of its regressors.

Instead of the weighted sum that represents a linear mapping, the nonlinear ARX model has a more flexible nonlinear mapping function:

$$y_p(t)=f(y(t-1),y(t-2),y(t-3),\ldots,u(t),u(t-1),u(t-2),\ldots) \tag{3}$$

Where f is a nonlinear function. Inputs to f are model regressors. Nonlinear ARX regressors can be both delayed input-output variables and more complex nonlinear expressions of delayed input and output variables.

The nonlinear ARX model computes the output y in two stages: 1) Computes regressors from the current and past input values and past output data. 2) The nonlinearity estimator block maps the regressors to the model output using a combination of nonlinear and linear functions.

B. Nonlinear ARX System Identification

Parametric estimation is the process to estimate the parameters of the ARX model by an error criterion. The meature methods are least square method. Parametric estimation of the ARX model can be achieved by the MATLAB Toolbox. In the regressors tab, the input channels and output channels have delay set to 1 and No. of terms set to 2. The model output $y(t)$ is related to the input $u(t)$ via the following nonlinear autoregressive equation:

$$y(t)=f(y(t-1),y(t-2),u(t-1),u(t-2)) \tag{4}$$

f is the nonlinearity estimator selected in the nonlinearity drop-down list of the model properties tab, and is Wavelet Network by default. The number of units for the nonlinearity estimator is set to select automatically and controls the flexibility of the nonlinearity—more units correspond to a more flexible nonlinearity.

IV. EXPERIMENTAL RESULTS

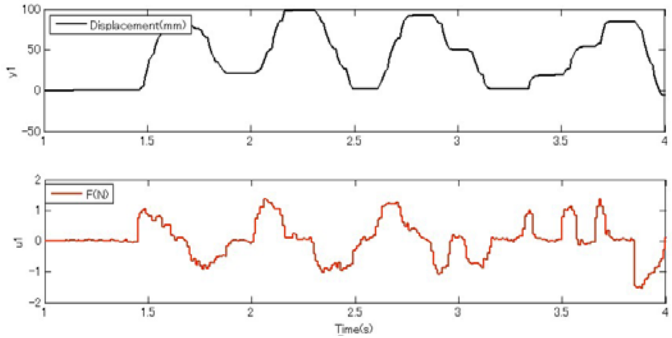


Fig.7 The input and output signals

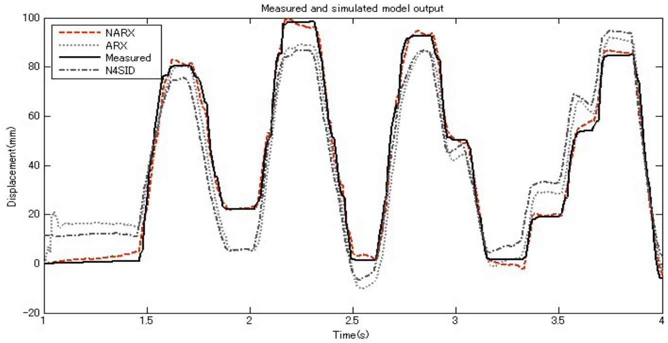


Fig.8 The measured and simulated model output

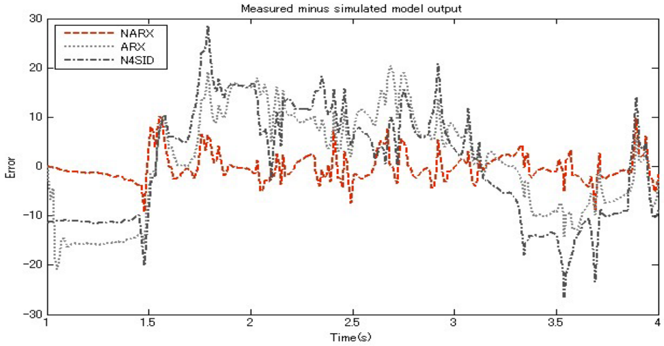


Fig.9 The measured minus simulated model output

A test method simulating the actual system is designed to examine the dynamic characteristics. In the surgeon console side, we pull the handle as axial movement. The loadcell will be used to measure the pull force, meanwhile, encode locals inside the stepping motor will record the axial displacement back to the DSP. The input force and output displacement is shown in Fig.7. System identification is then proceeded towards the input/output signals by system identification tool box inside the Matlab software, so as to obtain the dynamic characteristics. We enter the values of the signals and the sampling frequency (0.01ms) into the identification tool box, select the Nonlinear ARX model as the system identification method, set the model properities as Wavelet Network, set the search method as Adaptive Guass-Newton and choose the estimation focus on the prediction. Finally, to ensure the accuracy, comparison with measured value is made between Nonlinear ARX and the other methods (Linear ARX, N4SID) inside the tool box, shown in Fig.8 and Fig.9. It can be seen that the Nonlinear ARX is the smallest difference between the simulated and measured results. The autocorrelation function for the residuals as well as the cross correlation function between input and residuals are computed and displayed in the Fig.10.

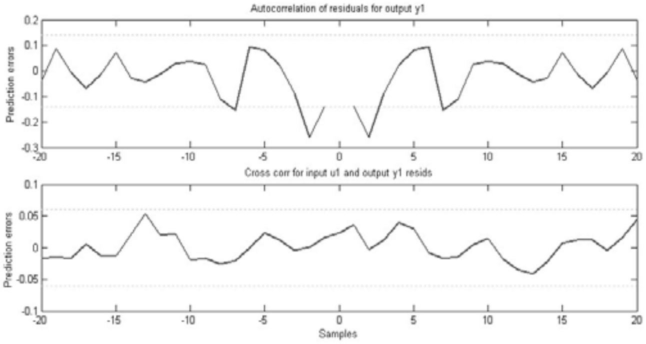


Fig.10 The residual analysis of the NARX model

V. CONCLUSIONS

In this paper, a novel robotic catheter manipulating system 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 master and slave side 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. Based on the Nonlinear ARX model， system identification has been done. It can calculate precisely the system equations, resonant frequency and damping ration to verify the specifications provided by the manufactures.

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.

ACKNOWLEDGMENT

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REFERENCES

[1] http://www.hansenmedical.com/home.

[2] Govindarajan S, Thenkurussi K and Xinyan L, “Design and fabrication of a robotic mechanism for Remote Steering and Positioning of Interventional Devices’’, *International Journal of Medical Robotics and Computer Assisted Surgery*, vol. 6, no. 2, pp: 160-170, 2010.

[3] Carlo P, Gabriele V, Francesco M, Filippo G, Patrizio M, Simone G and Nicoleta S, Simone S, Alessandra M, Giuseppe A, Laura L, Andreina S, Vincenzo S, “Robotic magnetic navigation for atrial fibrillation ablation’’, *Journal of the American College of Cardiology*, vol.47, pp: 1390-1400, 2006.

[4] http://catheterrobotics.com/CRUS-main.htm

[5] http://www.magnetecs.com/

[6] http://www.stargen.eu/products/niobe/

[7] Yogesh T, Jeffrey S. B, David W. H and Maria D, “Design and performance evaluation of a remote catheter navigation system’’, *IEEE Transactions on biomedical engineering*, vol.56, no.7, pp: 1901-1908, 2009.

[8] Arai F, Fuji R and Fukuda T, “New catheter driving method using linear stepping mechanism for intravascular neurosurgery’’, *Proceedings of the 2002 IEEE International Conference on Robotics and Automation*, vol.3, pp: 2944-2949, 2002.

[9] Walid S, Vivek Y. R, Oussama W and Jennifer E. C, et.al, “Atrial fibrillation ablation using a robotic catheter remote control system: Initial human experience and long-term rollow-up results’’, *Journal of the American College of Cardiology*, vol.51, pp: 2407-2411, 2008.

[10] Nainggolan L, “First look at robotic catheter system for AF ablation’’, *Arrhythmia-Electrophysiology (e-magazine)*, 2008.

[11] J Peirs, J Clijnen, D Reynaerts, H .V. Brussel and P Herijgers, B Corteville, et. Al, “A micro optical force sensor for force feedback during minimally invasive robotic surgery’’, *Sensors and Actuators A: Physical*, vol.115, pp: 447-455, 2004.

[12] Jian Guo, Shuxiang Guo, Nan Xiao, Xu Ma and Shunichi Yoshida, Takashi Tamiya, Masahiko Kawanishi, “A novel robotic catheter system with force and visual feedback for vascular interventional surgery’’, *International Journal of Mechatronics and Automation*, vol.2, No.1, pp.15-24, 2012..

[13] Yili Fu, Anzhu Gao, Hao Liu and Shuxiang Guo, “The master-slave catheterisation system for positioning the steerable catheter’’, I*nt. J. Mechatronics and Automation*, vol.1 (3/4), pp:143-152, 2011.

[14] Nan Xiao, Shuxiang Guo, Jian Guo and Xufeng Xiao, Takashi Tamiya., “Development of a kind of robotic catheter manipulation system’’, *Proceedings of the 2011 IEEE International Conference on Robotics and Biomimetics,* pp. 32-37. Phuket, Thailand, 2011.

[15] Jian Guo, Shuxiang Guo, Nan Xiao and Shunichi Yoshida, Takashi Tamiya, Masahiko Kawanishi, “Characteristics evaluation of the novel robotic catheter system’’, *Proceedings of the 2011 IEEE International Conference on Robotics and Biomimetics,* pp.258-262, Phuket, Thailand, 2011.

[16] Jian Guo, Shuxiang Guo, Nan Xiao, Xu Ma and Shunichi Yoshida, Takashi Tamiya, Masahiko Kawanishi, “Feasibility study for a novel robotic catheter system’’, *Proceeding of the 2011 IEEE International Conference on Mechatronics and Automation*, pp.205-210, Beijing, China, 2011.

[17] Nan Xiao and Shuxiang Guo, “Design and simulation of a MRAC controller for a human-scale tele-operating system’’, *Proceeding of the 2011 IEEE International Conference on Mechatronics and Automation*, pp.1843-1849, Beijing, China, 2011.

[18] Xu Ma, Shuxiang Guo, Nan Xiao and Jian Guo, Shunichi Yoshida, “Development of a novel robot-assisted catheter system with force feedback’’, *Proceeding of the 2011 IEEE International Conference on Mechatronics and Automation*, pp.107-111, Beijing, China, 2011.