Remote Catheterization Using a New Robotic Catheter Manipulating System

Xu Ma*, Shuxiang Guo, Nan Xiao, Baofeng Gao, Jin Guo

Intelligent Mech. Systems Eng. Depart.
Kagawa University
2217-20, Hayashi-cho, Takamatsu, 761-0396, Kagawa, Japan
s10d641@ stmail.eng.kagawa-u.ac.jp, guo@ eng.kagawa-u.ac.jp

Takashi Tamiya and Masahiko Kawanishi

Department of Neurological Surgery, Faculty of Medicine
Kagawa University
1750-1 Ikenobe, Miki-cho Kida-gun, 761-0793, Kagawa
{tamiya,mk}@med.kagawa-u.ac.jp

Abstract - **Manual operation of steerable catheter is inaccurate in minimally invasive surgery, requires dexterous and efficient manipulation for the catheter and exposes the surgeons to intense radiation. A novel robotic catheter manipulating system has been developed to reduce the performance error and irradiation to surgeons. In addition, unlike the conventional technique which requires surgeons to manipulate the catheter using their hands, remote systems always have removed surgeons' hands and replaced from joystick and handle, thus withdrawing their unique skills and experience. The novel robotic catheter manipulating system proposed that surgeon could manipulate the catheter that is same to the surgeries' often use. The surgeon console (the master side) used to measure the axial and radial motions of input catheter and the catheter manipulator (the slave side) used to implement to patients. Synchronization between the master and slave side had been tested. The experimental results showed the system has the ability to be a training system for surgeons and also facilitate the interventional surgery in the future.**

Index Terms - Minimally Invasive Surgery, Remote Operation, Catheter Manipulating System, Surgical Robotics.

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 on 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. 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], [18].
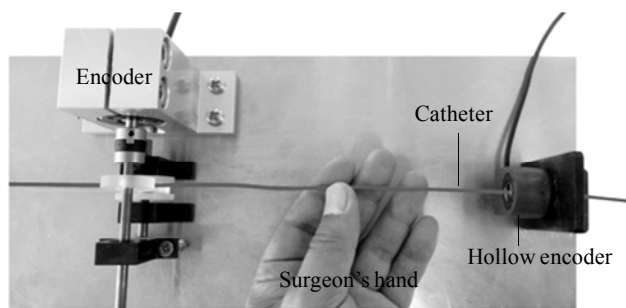
(a) The surgeon console
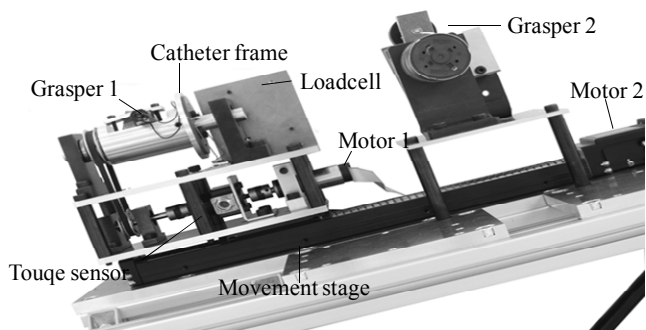
(b) The catheter manipulator
Fig.1 The robotic catheter manipulating system

Unlike the conventional bedside technique, which requires surgeons to manipulate a catheter using their hands, employment of these remote manipulating systems removes the catheter from the surgeon's hands, thus removing his/her dexterous and intuitive skills from the procedure. Furthermore, the technological complexities of these systems may require long training times to ensure that the surgeons are skilled in their use. For example, a study conducted by Schiemann *et al.* [20] demonstrated that equivalent navigation efficacy was achieved when comparing conventional navigation to remote navigation using the Niobe system in a glass phantom, after six months of surgeon training on the system. Therefore, it should be beneficial if a catheter manipulating system incorporated the dexterous skill set of an experienced surgeon during the procedure.

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 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 described in Fig. 1(a), using two motion-sensing devices via control unit DSP to communicate the position and rotation information with slave

side. The results of synchronization experiments had to evaluate the accuracy and precision of sensed and replicated motions.

II. ROBOTIC CATHETER MANIPULATING SYSTEM

The catheter manipulating system was 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 would 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 was built between the surgeon console and the catheter manipulator, the sketch map of the communication is shown in Fig.2. The surgeon console side sends axial displacement and rotational angle of the catheter to the catheter manipulator. At the same time, the catheter manipulator sends force information back to the surgeon console. 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], [19].
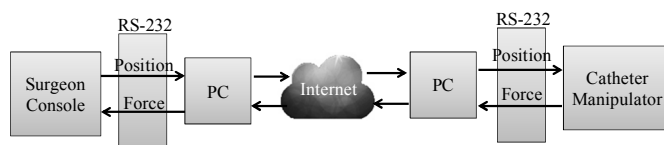

Fig.2 The communication sketch map

To ensure remote operation using this system is appreciable with conventional bedside operation, the following criteria were used in the design process.

1) The system should be compatible with generic 6-7F (diameter: 2-2.3mm) catheters, sizes common in interventional surgery.
2) Axial motion and radial motion should not be hindered by either the surgeon console and catheter manipulator.
3) Accuracy of axial movement: 1mm for 1.5m catheter
4) Accuracy of radial movement: below 3^0
5) Synchronization performance between surgeon console and catheter manipulator

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 radial direction 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 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 radial 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 be rotated by motor 1 when the catheter is fixed on the frame by grasper1.
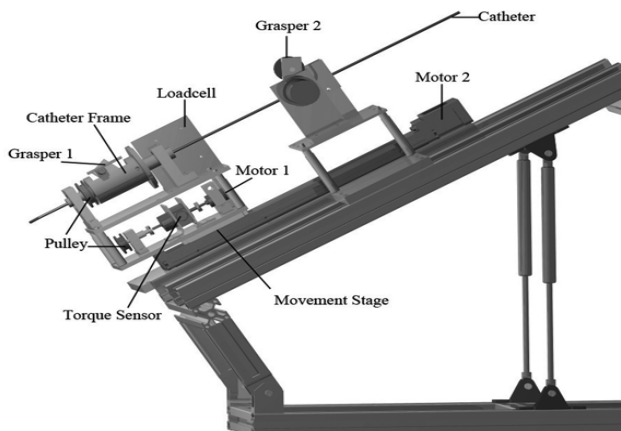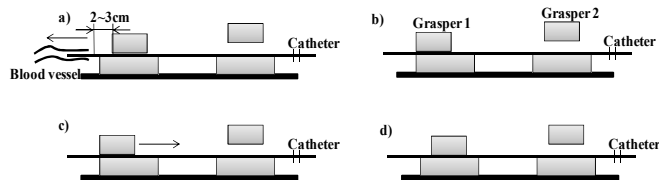

Fig.3 The catheter manipulator

Fig.4 The insertion motion

Torque sensor is applied in this system to measure the torque information during the operation. The torque information will be sent to the surgeon console and generate a torque feedback to the surgeon. The torque sensor is linked to motor 1 and the shaft 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 back to the surgeon console and generated a haptic feedback to the surgeon. To measure the resisting force, a mechanism is designed as shown in Fig.5 in details. 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 [21], [22].

B. The Surgeon console

The prototype of surgeon console shown in Fig.6 is an electromechanical device that measures the axial and radial motion of the input and output catheter using two mechanically independent passive sensors. Each sensor contains a 2000 lines encoder, mechanically coupled to the catheter. Axial position of the catheter is measured using a mechanical structure that converts the axial motion of the catheter to a rotational motion of the shaft of an optical encoder (Rotary encoder, MES2000P, Japan) using two rollers which mechanically couple to the catheter described in Fig.7 (a). One of the rollers (the main roller1) is directly coupled to the encoder, while the second idler roller2 passively ensures continuous contact between the primary roller and catheter. The position of the second roller is adjustable to allow variable contact friction between the catheter and the primary roller. The rollers were manufactured from MISUMI Corporation to ensure dimensional stability and the material is rubber. The axial position of the input catheter's shaft is determined as the product of roller circumference (approximate 75 mm). In the current implementation, detection of a single-counter increment yields a motion sensitivity of about 0.04 mm/count in the axial direction.
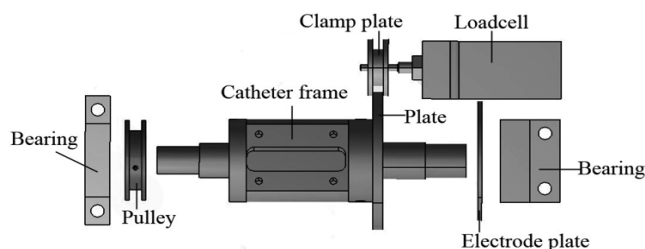

Fig.5 The force measurement mechanism

To measure radial motion, the catheter is used as a shaft to be coupled with the radial encoder shown in Fig.7 (b). A kind of hollow encoder (Rotary encoder, UN2000C4, Japan) is constructed to house catheter and coupling, which housed one screw. We processed the circular catheter into a irregular shapes, then the screw (diameter 2mm) can grip the catheter in the radial direction and holds it at the center of the encoder disk while allowing it to move freely in the axial direction; also, the screw which can be adjusted freely are loaded to ensure contact between the coupling and catheter. The outer edge of the coupling matching with hollow encoder enables the catheter to freely rotate the optical disk through the optical sensor. The radial position of the catheter can be measured directly by the encoder. In the current manipulation, detection of a single-counter increment yields a motion sensitivity of 0.18°/count in the radial direction.

C. Control of the system

Control of the surgeon console and catheter manipulator is achieved through two DSPs (TI, TMS320F28335) via RS-232 serial communication. Control software was implemented using C language, to enable synchronized motion control in the axial and radial direction, device control was multithreaded. The axial and radial motions measured by two

encoders in the surgeon console are represented for $P_{Surgeon}$ [X_M Θ_M] and solved to determine the corresponding position $P_{Patient}$ [X_S Θ_S] of the catheter manipulator in motor space. The position of each component of surgeon console is sampled at 1ms intervals; the corresponding velocity and acceleration values are determined and commands are then transmitted to the catheter manipulator controllers at 10 ms intervals. In the catheter manipulator side, the PD control algorithm has been added to improve the tracking accuracy.
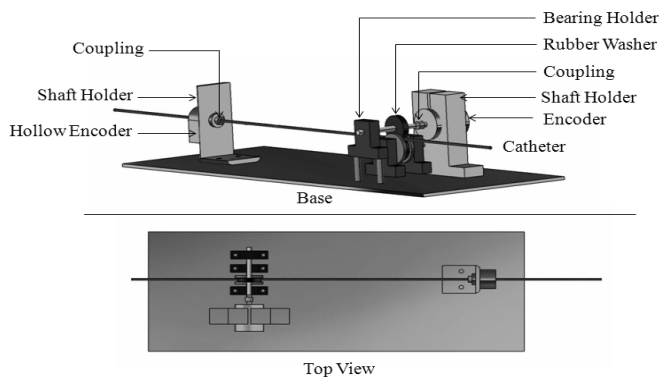
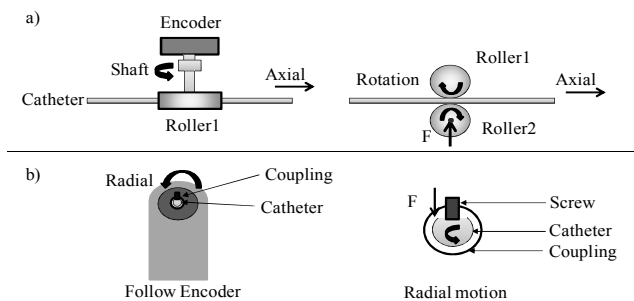

Fig.6 The structure of the surgeon console

Fig.7 The schematic diagram of surgeon console

III. METHOD

A. The synchronization performance

The delays of remote control can vary randomly and depend on the traffic conditions during the transmission times, thus making the representation of systems more complex. This difficulty is increased by the presence of package losses and vacant samplings.

In this paper, the synchronization experiments were carried out by using the catheter manipulating system. We just evaluated the tracking performance of the axial and radial displacement. The arrangement consists of a plant, with its sensor and actuator as shown in the Fig. 8. Due to the difficulty for controlling and measuring the network-induced delay in a real network, the network link between the master and slave is replaced by two delay generation structures, whose role is to collect the values in its input and transfer these values to its output, with controlled delays. These units of delay generation are composed of two first in first out (FIFO) buffers, one for the measured values and the other for control signal values. In this structure, all units have identical sampling period and the synchronization is guaranteed by the

local and integrated arrangement of the elements. The sensor is time-driven and the actuator is event-driven, where the event is the arrival of a new control signal. At each sampling instant, measured values are added to buffer 1 and then transfer these to buffer 2. Thus, it can keep the synchronization both two sides.

Catheterization procedures are very commonly performed for diagnosis and treatment of diseases of the heart and vascular system. The catheterization procedure is generally initiated by inserting a catheter into a blood vessel in the patient's body. The catheter is then guided to the desired location, most commonly in one of the heart vessels or elsewhere in the vascular system. For the remote control of robotic catheter system, the synchronization performance between the master side and the slave side need to be evaluated to ensure the insertion procedures can be transmitted accurately to the patients. Firstly, we advanced and retreated the catheter many times. Then, we obtained and compared the axial displacement by encoders both in surgeon console side and catheter manipulator side. Similarly, the synchronization of rotation could be obtained.
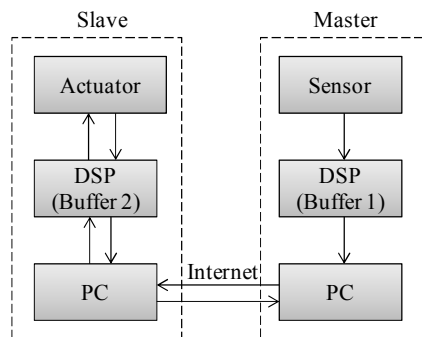

Fig. 8 Control loop with network delays

IV. EXPERIMENTAL RESULTS

A. The synchronization performance

In this experiment, we implemented synchronization experiment between the surgeon console and the catheter manipulator. The axial and radial displacement both of surgeon console and catheter manipulator was compared. Fig.9 showed the axial tracking experimental results. Similarly, the radial tracking experimental results was described in Fig. 10.

V. CONCLUSIONS

In this paper, a novel robotic catheter manipulating system was proposed. We developed a high precision mechanical system to assist surgeon completing the surgery procedures during the operation.

The presented system is a unique platform that provides the surgeon with the ability to use their dexterous skills while performing catheter interventions from a location remote to the patient. The presented experiments have demonstrated the system's ability to drive catheter axial and radial motions remotely. Combining remote navigation, implementation with the surgeon's skill makes this system as an effective approach to reduce surgeon's radiation exposure and physical

discomfort. In the future, utilizing this system to perform a range of interventional surgery in vivo is required in clinical practice.
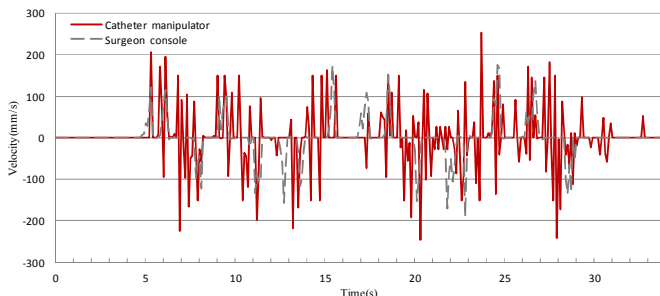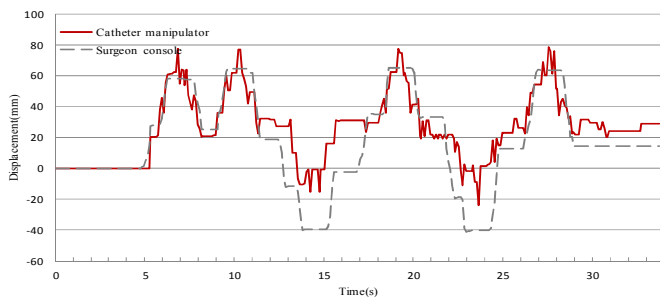

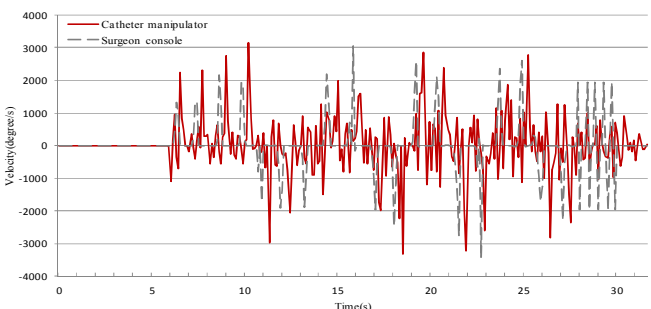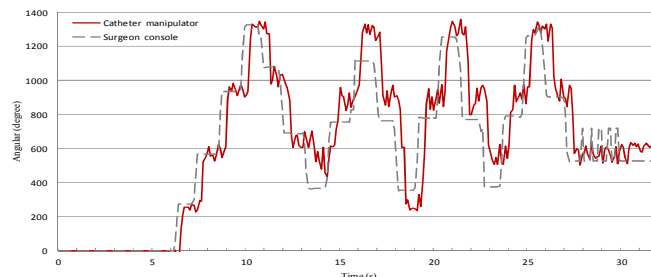Fig.9 The tracking trajectory of inserting motion

Fig.10 The tracking trajectory of rotating motion

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] Koa-Wing M, Kanagaratnam P and Wallace W, et al, "Initial experience of catheter ablation using a novel remotely steerable catheter sheath system'', Vol. 4, no.5, Heart Rhythm 2007.
[11] Tianmiao W, Dapeng Z and Liu D, "Remote-controlled vascular interventional surgery robot'', *Journal of Medical Robotics and Computer Assisted Sugery*, Vol.6, No.2, pp: 194-201, 2010.
[12] S. Ikeda, F. Arai, T. Fukuda, M. Negoro, K.Irie and I. Takahashi, et.al, "In vitro patient-tailored anatomaical model of cerebral artery for evaluating medical robots and systems for intravascular neurosurgery'', *IEEE/RSJ International Conference on Intelligent Robots and Systems*, Vol.2, No.6, pp:1558-1563, 2005.
[13] Nainggolan L, "First look at robotic catheter system for AF ablation'', *Arrhythmia-Electrophysiology (e-magazine)*, 2008.
[14] 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.
[15] 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.
[16] 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.
[17] 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, 2011.
[18] Baofeng Gao, Shuxiang Guo and Xiufen Ye, "Motion-control analysis of ICPF-actuated underwater biomimetic microrobots'', *International Journal of Mechatronics and Automation*, Vol.1, No. 2, pp. 79-89, 2011.
[19] Zhibin Song, Shuxiang Guo and Yili Fu, "Development of an upper extremity motor function rehabilitation system and an assessment system'', *International Journal of Mechatronics and Automation*, Vol. 1, No. 1, pp. 19-28, 2011.
[20] Nan Xiao, Jian Guo, Shuxiang Guo and Takashi Tamiya, "A Robotic Catheter System with Real-time Force Feedback and Monitor", *Journal of Australasian Physical and Engineering Sciences in Medicine*, Vol. 35, No. 3, pp. 283-289, 2012.
[21] Nan Xiao and Shuxiang Guo, "Modeling and Control of a Micro-operating mechanism for a Human-scale Tele-operation system", *International Journal of Robotics and Automation,* Vol. 27, No. 2, pp: 206-216, 2012.
[22] Xu Ma, Shuxiang Guo, Nan Xiao, Jian Guo, Shunichi Yoshida, Takashi Tamiya and Masahiko Kawanishi, "Development of a Novel Robotic Catheter Manipulating Systemwith Fuzzy PID Control", *International Journal of Intelligent Mechatronics and Robotics (IJIMR)*, Vol. 2, No. 2, pp. 58-77, 2012.