A Haptic Catheter Operating System Using Magnetorheological Fluids

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Abstract – Minimally invasive surgery and Therapy (MIST) is popular used both for diagnosis and for surgery. Teleoperation, a new kind of surgery, is used to protect the surgeon from X-ray radiation. However, some safety problem should be considered because the surgeon was separated from the patient remotely. A most effective address method is design of a haptic interface as a master console, which can provide the ‘immersive’ operation to the surgeon. In this paper, a new haptic interface is design for catheter operation surgery through controlling smart material-magnetorheological fluids. Magnetic field, haptic interface and haptic performance calibration mechanism have been designed and fabricated. Some experiments have been done to verify the efficiency of haptic interface, which can be used as master console as well as training simulator for non-experience surgeon.

Index Terms –Minimally Invasive Surgery and Therapy (MIST), Haptic Interface, Magnetorheological Fluids (MRFs), Stability, Transparency, Telerobotics, Catheter Operating System.

I. INTRODUCTION

Minimally invasive surgery and Therapy (MIST) is a revolutionary surgical technique and have some advantages over conventional open surgery. The main advantages of this technique is that the amount of trauma involved in MIST is far less than on conventional surgery because the incision is very small, result in reducing the patient recuperation time and the burden of long time hospital stay and surgery cost [1]-[3].

In recently, with the quickening pace of modern life, in most industrialized nations, the incidence of cardiovascular and cerebrovascular disease has been increased. Catheter ablation and catheter intervention for diagnosis is one of the most significant advances in MIST. Catheters are long and thin flexible tubes and wires are inserted into the vascular system requires precise manipulation for success. There are several challenges to successful complete this kind of surgery: the first challenges characteristic of difficult ablation or diagnosis procedures include long procedure times, extended fluoroscopic exposure to the patient and physician [4], since X-ray are often used during catheter surgery in neurology, cardiology, urology and cerebrum vascular to track the position of the catheter inside the body of the patient [5]. To address this problem, catheter-driving mechanisms have been developed for telesurgery, such as using feeding rollers and linear stepping mechanisms (LSMs) to provide surgical tools to drive the catheter [6], and a new prototype of a microcatheter with an active guide wire that has two bending degrees of freedom and is made using ionic conducting polymer film (ICPF) with a shape memory alloy (SMA) actuator fixed at its end to act as a servo actuator [7]-[8].

In the context of several kinds of catheter operating mechanisms designed (as slave system placed beside the patient), the master console (placed in remote physician site) was fabricated according to the slave requirements. On this bases of master-slave mechanism, teleoperation system used in MIST become a promising research field. A teleoperation MIST system consists of a human operator, a master haptic device, a communication and control channel, a remotely located slave manipulator and the patient. In such systems, there is a need information exchange between the human operator and the remote manipulator. The information can be in the form of either position (velocity) or force [9].

So it is important to design a force-reflecting master-slave system during teleoperated MIST system. Kinesthetic or force feedback system measured or estimated the forces applied to the patient through slave surgical instrument, and provided the force feedback to the physician’s hand via a haptic interface. Such device can significant improve the safety of the surgery.

Haptic generally describes touch feedback, which may include kinesthetic (force) and cutaneous (tactile) feedback. In open surgery, physicians can feel the interaction of the instrument and the tissue of the patient, which can provide force cues. But in manual MIST or teleoperation, the tactile and kinesthetic cues may be masked. Some studies reported that the lack of significant haptic feedback increased intraoperative injury [10]. During the teleoperation, all natural haptic feedback in eliminated since the surgeon no longer manipulates the instrument directly. The lack of effective haptic feedback is to be a major limitation of current MIST and teleoperated system [11].

Catheter operation system in MIST technical field has been active for several years. Two commercial available remote controlled catheter navigation system, Niobe® magnetic navigation system (Stereotaxis, USA) and Sensei® robotic navigation system (Hansen Medical, USA) have improved the operating environment for surgeons [12]. This research also has been done in university and research center. Such as robotically controlled cardiac catheter system for heart surgery was designed at Harvard University [13] (Robert D. Howe. et al. in Harvard BioRobotics Lab.) and a custom linear stepping
mechanism was designed by T. Fukuda et al. at Nagoya University [6].

Catheter teleoperated system research has been done at Guo Lab. in Kagawa University from 2007 to now. The first generation catheter teleoperation system was established. Phantom Omni was used as a master console, the surgeon operate Phantom to drive the mechanism of catheter operating system (the slave system) [14]. In order to increase the maneuverability of the catheter invention surgery, the second generation catheter teleoperation system was fabricated based on imitation the physician skills [15-20]. Force sensor was adopted in the slave manipulator system. The measured force can be feedback to the master side. The physician controls the slave manipulator insertion and rotation the catheter through operating a rod. Such master device is not only lack of sense of reality but inconformity with surgeon experience. So a new haptic robotic system for catheter operating using MR fluid has been provided in this paper.

This paper is organized as follows: magnetorheological fluids (MRFs) based haptic interface design is descripted in section II, concluding: MR fluids properties introduction and magnetic field and haptic interface as well as haptic calibration mechanism design. In section III, experiment description, at last, conclusions of the haptic interface design and future work.

II. SYSTEM DESIGN

In generally, a teleoperation surgical system as shown in Fig.1 consists of master system (console) and slave manipulator system (executing), in which the slave manipulator tracks the motion of the master device that is commanded by the surgeon and in which the measured force is fed back to the master device form the slave manipulator. The information concluding the force and position was exchanged bilateral between surgeon and patient. Considering the safety of the surgery, two necessary and sufficient conditions are required: stability and transparency. Stability can be guaranteed through the parameter adjustment in the master-slave system close loop control. Transparency means when the operator operating the master has the feeling of ‘direct’ interaction with the remote environment. Although system stability is contradiction with the system transparency, in the control theory point, a control system is required that improve the system transparency while keep system stability. The transparency of the master slave system can be expressed as follows:

\[ F_h = F_e \]  \hspace{1cm} (1)
\[ \dot{x}_m = \dot{x}_s \] \hspace{1cm} (2)

Where \( F_h \) is the force of the operator act on the haptic interface, \( F_e \) is the force measured by the force sensor attached on the slave manipulator when interact with the patient, \( \dot{x}_m \) is the velocity of the operator operating the haptic interface in the master site, \( \dot{x}_s \) is the velocity of the slave manipulator interacting with the patient.

In order to ensure the safety, it is significant important to design haptic interface for the teleoperator, which can display the force when the slave manipulator interacting with the patient.

**A. The Haptic Interface Based on Magnetorheological Fluids**

Magnetorheological (MR) fluids are a special class of rheological fluids (general called smart materials), which respond to an applied magnetic field with a change in rheological behavior. Typically this change is manifested by the development of a yield stress that monotonically increases with the applied field [21]. The MR fluid can be returned to its rheological state with in a millisecond when the applied field is removed.

MR fluids as a controllable fluid was used to mimic the compressional compliance of biological tissues in order to realized a haptic display for surgical training in MIST applications [22]. Some relative researches have been done in this field. Such as an encountered-type haptic interface using MR fluid for surgical simulators has been proposed by Tsujita T. et al. at Tohoku University [23], and two and five DOF MR fluid-based telerobotic haptic system was designed by Farzad A. et al. at the Ohio State University [24], and the Haptic Black Box ((HBB-I) and (HBB-II)) was designed to build shapes that can be directly felt and explored by the hand at University of Pisa by Rocco Rizzo et al.[25].

MIST begins with a needle puncture into, for example, the femoral artery or the vascular system. This procedure is common in clinical practice and diagnosis. Most of the procedures in the endovascular field, angioplasty or stenting, need an arterial catheterization. Catheter insertion can be harmful to the patient, because arterial or venous vessels are often surrounded, such as nerves can be easily damaged. Precise catheter insertion thus requires a perfect knowledge of the three-dimensional development of vessels and high level of dexterity avoiding vessel puncturing, skills which are only attainable through considerable practice [26]. Based on this idea, the haptic robotic system for catheter operation using MR fluid has been proposed to provide haptic sensation for the surgeon during teleoperation or for novice surgeon for training.
Magnetorheological fluids (MRFs) are materials that undergo in rheological behavior when an external magnetic field is applied. MR fluids are suspensions of micro-sized, magnetizable particles in the carried fluid. They mainly consist of three components [28]: magnetizable micro-sized particles, some additives, and carrier fluid (such as mineral oil, synthetic oil, water, ethylene glycol or vegetable oil). The magnetizable micro-sized particles induce polarization upon the application of an external magnetic field, which results the viscosity of MR fluids. The additives include stabilizers and surfactants. The stabilizers serve to keep the particles suspended in the fluid because particle sedimentation would greatly decrease the behavior of MR fluid [29], and the surfactants are adsorbed on the surface of the magnetic particles to enhance the polarization induced in the suspended particles upon the application of the magnetic field. The carrier fluid serves as a dispersed medium and ensures the homogeneity particles in the fluid.

In the absence of an applied field, MR fluids exhibit a Newtonian-like behavior randomly in the carried fluid, where the shear stress $\tau$ below the yield stress $\tau_y$ (at strains of order 10-3), the material viscoelasticity characteristics can be expressed as Equation [30]:

$$\tau = \eta \dot{\gamma}, \quad \tau < \tau_y$$

When the application of magnetic field, MR fluids align themselves forming into chain state structure (semi-solid state) that resists shear deformation or flow in the direction of the field, which exhibit a variable yield stress is often represented by the Bingham behavior, where the shear stress of MR fluids is governed by Bingham’s equation:

$$\tau = \tau_y + \eta \dot{\gamma}, \quad \tau > \tau_y$$

Where the shear stress $\tau$ above the yield stress $\tau_y$, the shear stress is governed by the Equation (4). The Bingham plastic model has proved useful in the design controllable fluid-based device. However, the controllable fluid behavior usually exhibits some extent different from this model. By increasing or decreasing the intensity of the magnetic field, the interaction among the particles and rheological properties (e.g. viscosity) can be easily altered continuously [27].

### Table I

**MRF-122EG Typical Properties**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Appearance</td>
<td>Dark gray liquid</td>
</tr>
<tr>
<td>Viscosity, Pa-s @ 40°C (104°F)</td>
<td>0.042 ± 0.020</td>
</tr>
<tr>
<td>Calculated as slope 500-800 sec-1</td>
<td></td>
</tr>
<tr>
<td>Density, g/cm³ (lb/gal)</td>
<td>2.28 (2.48)</td>
</tr>
<tr>
<td>Solids Content by Weight, %</td>
<td>72</td>
</tr>
<tr>
<td>Flash Point, °C (°F)</td>
<td>&gt;150 (&gt;302)</td>
</tr>
<tr>
<td>Operating Temperature, °C (°F)</td>
<td>40 to +130 (~40 to +266)</td>
</tr>
</tbody>
</table>

Typically, the diameter of the magnetizable particles range from 1 to 5 microns. Commercial quantities of relatively inexpensive carbonyl iron are generally limited to 1 or 2 microns. Smaller particles that are easier to suspend in the carried fluid especially fit for application in small force haptic-interface used in surgical training system as well as the response times about several microsecond when the magnetic field is removed. In this paper, MR fluid (MRF-122EG) was used to form into the haptic-interface, which is the product of the Lord Corp. and it’s typically properties described in Table I. Some haptic devices based on Electrorheological Fluids (ER fluids) are reported in literature [33]-[34].

In conclusion, a semi-active passivity encountered-type of haptic-interface based on magnetorheological fluid (MR) is made in this study, because these advantages of MR fluids are over the ER fluids.

### C. The Force Generated Principle

A therapeutic cardiac catheterization is that a physician will use special techniques and a thin plastic spaghetti-like tube or catheter to insert the heart from blood vessels in the legs or the neck and to widen a narrowed vessel or stiff valve, close abnormal blood vessels and so on (such as, heart defect) instead of opening the chest and heart. This kind of surgery needs high operating techniques and has a good understanding of the insertion force or rotation torque felt by the expert physician. In this haptic interface, the non-experience physician can operate a catheter to do some training through insertion or rotation catheter through the MR fluids. He or she will have a good feeling just like really catheter operation surgery on condition that the viscoelasticity of the MR fluid is good controlled. The scheme description of catheter insertion or rotation through in the MR fluids is shown in Fig.2.

![Fig.2 Scheme description of affine deformation of a chain of spherical particles](image)

### D. The Fabricated Magnetic Field

Magnetic field providing to the MRF fluids is generated by two coils shown in Fig.3. The parameter of the coils is shown in Table II. As shown in Fig.3, Three pieces of spacer (each of spacer is 4mm) were designed to adjust the gap of two coils, so the gap between two coils in the height direction can be adjusted to meet the requirement of the container size design. Diameter of the copper wire of the coil is 1.6mm and each of coil turns is 1200T. The bobbin of the coil and the stage are made of aluminum. Cylinder with circular truncated cone made of SS400 steel is used to increase the magnetic field in the center. The yoke used to support the coils is also made of Japanese
industrial standards (JIS) SS400 steel, all others components are made of non-magnetic material.

<table>
<thead>
<tr>
<th>Parameter item</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper wire diameter (mm) (AIW)</td>
<td>Ø1.6</td>
</tr>
<tr>
<td>Inner diameter of the coil (mm)</td>
<td>Ø30</td>
</tr>
<tr>
<td>Outer diameter of the coil (mm)</td>
<td>Ø119</td>
</tr>
<tr>
<td>Height of each coil (mm)</td>
<td>68</td>
</tr>
<tr>
<td>Coil turns (T)</td>
<td>1200</td>
</tr>
<tr>
<td>Coil 1 resistance (Ω)</td>
<td>2.435</td>
</tr>
<tr>
<td>Coil 2 resistance (Ω)</td>
<td>2.448</td>
</tr>
</tbody>
</table>

### Table II

#### MAGNETIC FIELD PARAMETERS

**E. The Developed Catheter Haptic Interface**

The whole mechanism of the haptic interface is shown in Fig.4. In telerobotic surgery system (in general, master-slave system structure is usually adopted), telepresence as well as operated the real surgical instrument not instead of by operating the stick or Phantom are significant important to ensure the safety of the catheter intervention for the physician operate the haptic interface in the remote master site. The dexterity and multi DOFs are the basic requirements of robotic training system design to provide real training scenarios. The physician can operate the catheter freely just like operating the catheter beside the patient side through operating this haptic interface. Therefore, it can be used for training the inexperience.

**F. The Haptic Interface Calibration Mechanism Design**

The haptic-interface has been designed, the physician operated the catheter insertion and rotation can feel the resistance force just like the really surgery operated on the patient. The calibration mechanism is designed to evaluate the haptic performance.

When the physician operated the catheter, he or she will felt the resistance force provided by the friction between the catheter surface and MR fluids. In order to measure the provided resistance force felt by the physician, the haptic calibration mechanism was designed and shown in Fig.5. During this measurement system, the physician operating catheter is instead of by the calibration mechanism, which mainly consists of stepping motor and load cell (made in TEAC Corp., in Japan). The stepping motor, which is controlled forward and backward, is used for insertion the catheter instead of physician operating. The load cell is fixed on the load cell bracket. The motor stage is used for fixed the stepping motor.

**Fig.5 The whole structure of haptic interface calibration system**

### III. EXPERIMENTAL RESULTS

Experiments were performed by using one degree of freedom haptic calibration system. The experimental set up block diagram is shown in Fig.6.

**Fig. 6 Haptic performance measurement experimental setup**
The haptic performance measurement experimental setup is shown in Fig. 6. It consists of three parts: the first part is the magnetic field generation and control. The magnitude of magnetic field intensity is controlled through adjustment and amplifying the current to supply the magnetic generator. The second part is the haptic calibration system which consists of a catheter insertion stepping motor system (VEXTA, ASM46AA, DC: 3.42V, 0.9A, Oriental Motor Corp., Japan) control. The current control signal is amplified by the stepping motor driver and controller (EMP400 Series Controller, Oriental Motor Corp., Japan). The third part is the resistance force (haptic sensation) measurement device, which formed by a load cell and strain amplifier (SA-570ST, TEAC, Japan).

The experimental evaluation method is illustrated in Fig.7. The force measured by a force sensor attached on patient-manipulator in the slave is transmitted to the haptic interface in the form of reference current, which is exchanged by the relationship of between the force and the current input. The relationship is dependent on the design of the magnetic generator and the characteristic of the MR Fluids. Experiments have been done here to find the relationship between the force and the current.

In order to find the relationship between coil current and the haptic force, different coil currents in the range of 0-2[A] with a step 0.20 [A] are applied to the each coil. In this experiment, the coil current is set as constant value without feedback. In order to control the haptic force accurately according to reference force measured by the patient-manipulator, force feedback control between haptic interface and patient-manipulator is indispensable.

The relationship between the haptic force and the input current

In order to provide a haptic display to the physician, the viscoelasticity of the MR fluids is needed to be controlled accurately. That is to say, the magnetic field intensity needs controlled accurately. So the experiments have been done to find the relationship between the coil current and the magnetic intensity of the magnetic generator. TM 701 is used as magnetic intensity measurement device (made by KANETEC Corp. in Japan). The magnetic sensor of TM 701 is placed in the center of the magnetic generator. When the current is changed step by step, each step is 0.20A. The changed range is from 0 to 2.00A. The relationship between the magnetic intensity and the coil current is shown in Fig.9.
IV. CONCLUSIONS AND FUTURE WORK

Minimally invasive surgery and Therapy (MIST) is popular used both for diagnosis and for surgery. Teleoperation, a new kind of surgery, is used to protect the surgeon from X-ray radiation. However, some safety problem should be considered because the surgeon was separated from the patient remotely. A most effective address method is design of a haptic interface as a master console, which can provide the ‘immersive’ operation to the surgeon. In this paper, a new haptic interface is design for catheter operation surgery through controlling smart material-magnetorheological fluids. Magnetic field, haptic interface and haptic performance calibration mechanism have been designed and fabricated. Some experiments have been done to verify this kind of haptic interface, which can be used as master console as well as training simulator for inexperiance.

In future, in one side, a motion measurement device will be combined into the design haptic interface to form into the haptic master system. In another side, a slave manipulator will be designed to form into master-slave system. Time delay always exists in teleoperation communication; therefore, teleoperation experiments with time delay consideration will be done to further verify the designed haptic interface.

REFERENCES