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# A Robotic System with Force Feedback for Micro-Surgery*

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**Abstract - A robotic system with force feedback for micro-surgery is developed (named "Microhand"). The system designed is based on a master-slave operation mode. The slave manipulators are designed by using macro-micro frames. The PHANToM Desktop developed by the SensaAble Technology Company is used as the master device. The interactive force/torque information of the slave manipulators and the surgical environments measured by the six-dimension force/torque sensors are fed back to the master device, so that the system is capable of providing force feedback to the surgeon during operations. The validity of the system has been proved through animal experiments of vas suturing a rabbit's 3mm in diameter neck artery and its 1mm in diameter leg artery.**

**Index Terms – medical robot, force feedbacks, master-slave micro-surgical operation**

## I. INTRODUCTION

In recent years, more and more researchers have focused on the study of robot assisted surgical system [1]. The two representative surgical systems in minimally invasive surgery (MIS) have got authentication from the American FDA [2]. In micro-surgery, a handheld microsurgical instrument facet developed by Carnegie Mellon University is being researched toward active cancel tremor [3]. With the micro-surgical robot system, Misuishi et al have implemented tele-operation by internet, and finished a 1mm vas suturing 700km away [4]. However, force feedback information during the micro-surgery operation was not put into consideration in this system.

A robotic system with force feedback for microsurgery, called MicroHand ("Miaoshou" in Chinese), has been developed in our lab. A master-slave control mode is adopted in the system. The slave manipulators (both left and right hands) of Microhand system have cable driven structures. On the end of the slave manipulators are a six-dimension F/T sensor Mini40 and terminal operation tools, which are safe and easy to be replaced. Two sets of Phantom Desktop developed by the American SensaAble Technology company act as the master manipulators. The MicroHand system can be used to perform operations, such as cutting, gripping, suturing and knotting and so forth. It has been used succeeded in assisting the operation of vas suturing a rabbit's neck artery (3mm in diameter) and its leg artery (1mm in diameter).

Six sections are included in this paper: 1) overview of the MicroHand system;2) design of the slave manipulators; 3) master system and force feedback; 4) kinematic analysis of master/slave system; 5) control and multi-view image system; 6) animal experiments.

## II. OVERVIEW OF THE MICROHAND SYSTEM

The MicroHand System consists of master-slave manipulators (both left and right hands), various changeable surgical tools, force sensors, a controller, and a multi-view image system, as shown in Fig.1. Each slave manipulator has a macro motion mechanism with 2 DOF and a micro motion mechanism with 6 DOF. The macro and micro mechanism are separated; the former that provides large workspace is used to move the operative tools into the surgical fields rapidly, while the latter is designed for the realization of precise operations.

The prototypes of MicroHand system and the slave system are shown in Fig.2a and Fig.2b respectively. The position and posture of precision-motion mechanisms of slave manipulators are controlled by master manipulators. Master manipulators are the commercial haptic interface (PHANToM Desktop). The terminal tools on the slave manipulators possessing the open-close function are controlled by the switch button on the stylus of PHANToM. The six-dimension F/T sensor is fixed at the

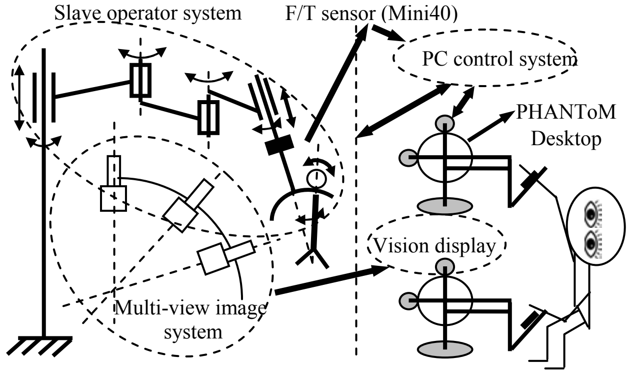


Fig.1 MicroHand system scheme

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Fig. 2a MicroHand system

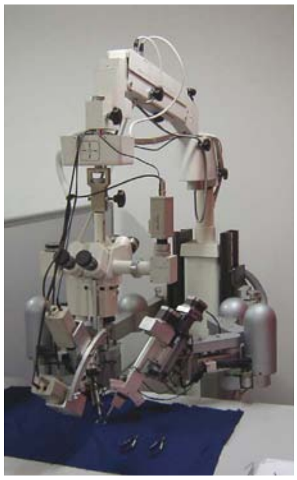

Fig.2b Slave system

end of the slave manipulators and can be used to detect the three-dimension forces and three-dimension torques, which are generated between the slave and the exterior surgical environment, Owing to Phantom Desktop restriction, the MicroHand system can only realize three-dimension force feedback without torque feedback between the master and the slave. The surgeon can feel the real interactive forces remotely. The performance parameters of this system are shown in Table I.

## III. Design of Slave Manipulators

The left and right hands of the MicroHand slave manipulators have the same structures and are installed on two sides of the column of the microscope systems respectively. As shown in Fig.3, the structure of the right hand can be divided into two parts. One is the macromotion mechanism including joint 1 and joint 2. The other is the micro motion mechanism involving joints 3 to 8. The micro motion mechanism has six-DOF, three for position (joint 3, joint 4 and joint 5) and three for posture (joint 6, joint 7 and joint 8). The posture of MicroHand consists of rotation and circular movement of the circular guide and rotation of the surgical tools. Because the three rotating axes intersect into one point, the position of the tip is kept steady when the postures of tools change.

TABLE I
Performance Parameters of MicroHand System

| Item | Performance |
|---|---|
| Macro operative range | 600×800×400mm$^3$ |
| Micro operative range | 100×200×40mm$^3$ |
| Resetting precision | ±0.01mm |
| Response Time | 10ms |
| Tremor | 0.01mm |
| Force-sensing precision(X/Y) | 0~20N±8% |
| Force-sensing precision(Z) | 0~60N±5% |

### *A. Cable Driven Structure*

To reduce the terminal weight of the slave manipulators and enhance the rigidity of the system, cable driven structures have been used both between joint 3 and joint 3’ and between joint 4 and joint 4’. As shown in Fig. 3 and Fig. 4, part II and part IV are cable driven structures, while part III is the transition shelf with belt driven structure. Wire wheel on joint 3 is fixed on arm I. Another one on joint 3’ is fixed on the transition shelf. When arm II rotates around arm I, wire wheel on joint 3’ will drive the transition shelf rotate in an inverse direction. Thus the posture changes can be compensated by cable driven structures as arm II rotates. Similarly, the wire wheel on

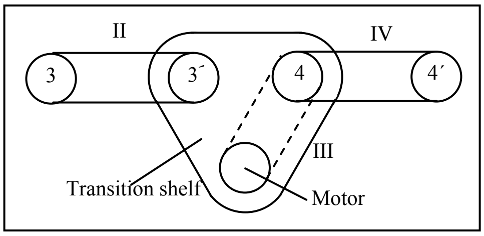


Fig.4 Cable driven diagram

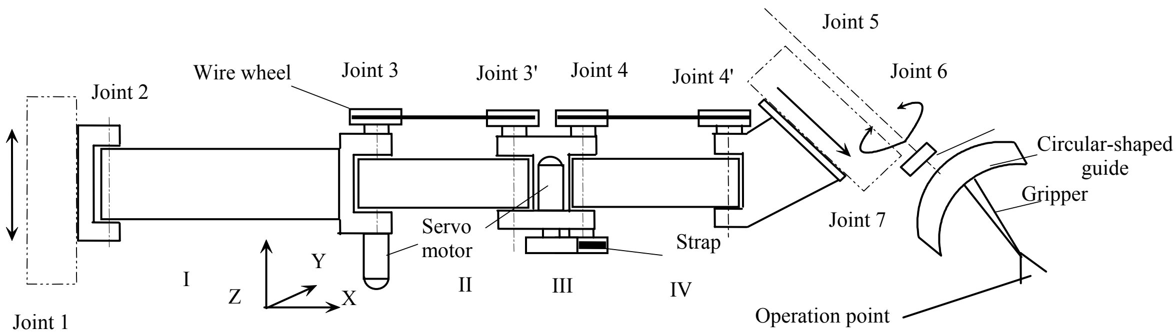


Fig.3 Overview of the slave

joint 4 fixed on the transition shelf and that on joint 4' is fixed on arm posture mechanism. In this way, the posture changes can be compensated by cable driven structures as arm IV rotates.

### B. *Surgery Tools for Microhand System*

Surgery tools include bistoury, scissors, forceps, needle holder etc, as shown in Fig.5a. In order to change the surgical tools, a quick-changed mechanism is designed to meet the requirements of surgical operations. Fig.5b shows the gripping mechanism of a gripper. In order to operate flexible tissue and organs, gripping mechanisms with torsion springs are used instead of conventional rigid mechanisms.

## IV. MASTER SYSTEM AND THE FORCE FEEDBACK

We selected PHANToM Desktop from the Sensable Technology Company as the master manipulators. Generally, PHANToM has a major application in the technology of VR [5]. It consists of six DOF for motion and three-dimension force feedback [6]. When it is applied to the MicroHand system, it is redeveloped to control the low-level toque motors and record the encoders in it directly.

As shown in Fig.6, firstly, the force of the exact position where Mini40 is installed is detected; Secondly, based on the force equilibrium model of the sensor and the terminal tool, we can calculate the forces on the terminal point; Thirdly, the forces of the terminal tools to the operating point of the PHANToM Desktop are mapped; finally, calculating the moment of each joint based on force equilibrium principles and multi-factor arithmetic. Thus, the surgeon can feel force feedback from master manipulator.

In operations, tissues under skin are often unnecessarily hurt due to surgeons' incapability of sensing tiny force. With help of MicroHand system, such damages might be avoided. An experiment has been performed on a rabbit. In the experiment, three positions in the process of cutting the rabbit's skin are marked in the Fig.7. $p_0$ is the position where the bistoury first contacts the skin, $p_1$ and $p_2$ represent the positions of cutting the skin and the muscle respectively. The position and interactive force of the slave manipulator are shown in Fig.8. The difference of interactive force between $p_1$ and $p_2$ is about 0.1N (as shown in Fig.8). Generally speaking, such difference is too tiny to be sensed. Magnification of this tiny force can improve the precision of the operation.

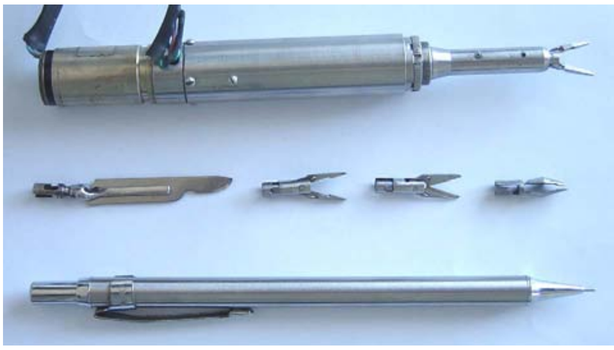

Fig.5a Prototype of surgery tools

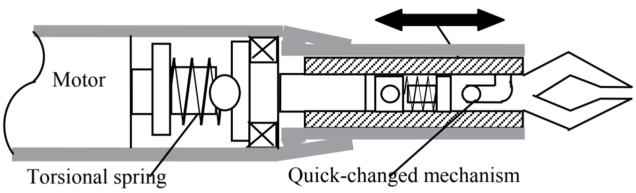


Fig.5b Schematic of gripper

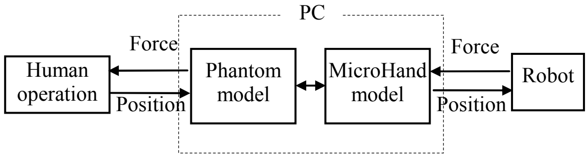


Fig.6 Close-loop of touch feeling

## V. KINEMATIC ANALYSIS OF MASTER-SLAVE SYSTEM

### A. *Isomery between Master-Slave*

Design for the slave manipulator is decided by the requirements of micro-surgical operations. However, the master manipulator as the human interface should be as comfortable as possible for surgeons to operate. These requirements result in isomery in mechanical structures between master and slave manipulators. Considering the problem of isomery, the joint motion of the slave

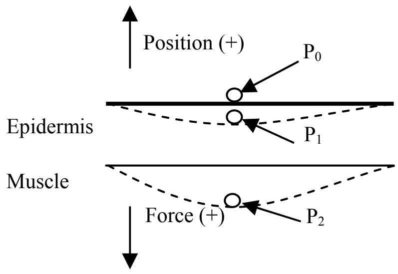


Fig.7 Position of cutting the rabbit's skin

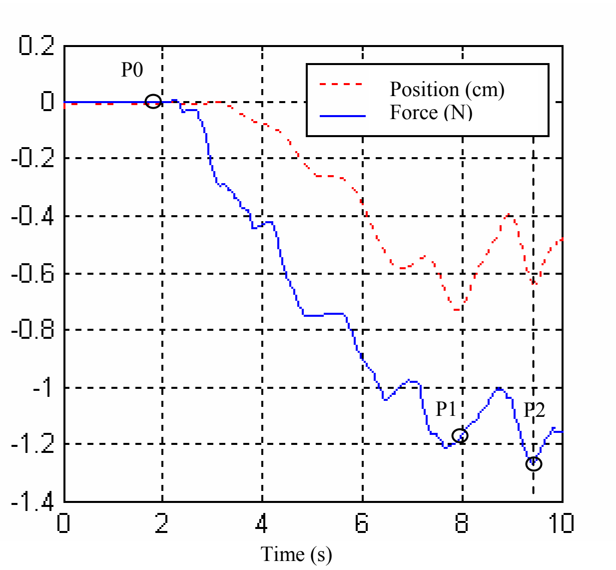


Fig.8 The position and interactive force of the slave manipulator

manipulators can not be controlled by commands from one joint motion of master.

To solve this problem, mathematical models of master and slave manipulators are constructed respectively. And then, according to the equivalent positions and postures in the inertial reference frame, kinematic relationship between them is established in order to realize the corresponding control.

*B. Inverse Kinematics and Linerazition of Slave Manipulators*

Inverse kinematics calculations of slave manipulator are required in the control algorithm. In the inverse kinematics procedure, lots of transcendental functions and singular values appear. The procedure increases the work of calculations and prolongs the response time between the masters and the slaves. It turns out to be the choke point of the control algorithm.

To speed up calculation, DSP is utilized to carry out high-speed data processing. In the minute time period Δt, the complicated inverse kinematics model of slave manipulators is linearized according to the inverse Jacobin algorithm. In Fig. 9, Δ and Δ′ represent the micro variation of the master and the slave in the inertial reference frame, respectively. Experimental results show that this algorithm is effective in reducing the amount of calculation.

*C. Error Analysis of Linearized Inverse Kinematic Model of Slave Manipulators*

The linearized model of the slave produces accumulated error in the simplification of calculations. Therefore, before the linearized model is applied, it is essential that influential factors be analysed thoroughly and the critical ones be determined.

*1) Tracking Error of Slave Manipulator*

In the MicroHand system, the tip of the slave manipulator tracks the trajectory provided by the master manipulator. During a very small period of time, the tip of the slave responds to the master's tiny displacement. Because the time interval Δt is constant and is decided by the controller, the distance λ that the slave has moved during Δt will affect the system interpolation accuracy. To decide the precision of the system, it is supposed that the system is operated in a very low speed. During the operation, the possible error is resulted from both the vibration amplitude of the surgeon's hands and the scale of MicroHand. Since the former is reported to be larger than

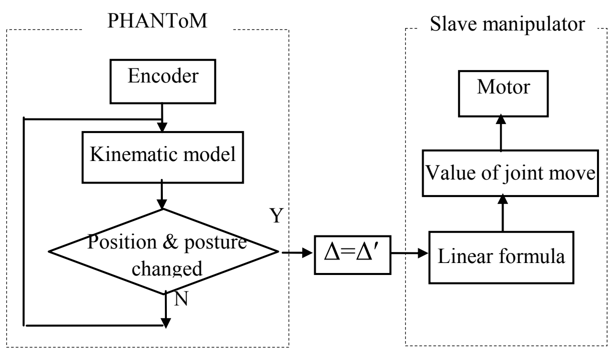

Fig.9 Master-slave data flow chart

0.5mm and the latter is 10:1, the minimal movement interval of the slave is 0.05mm, that is, λ=0.05. Considering λ=0.05, λ=0.1, and λ=0.2 respectively, the corresponding values of the accumulated error are shown in Fig. 10. It shows that the system errors are in proportion to the moving distance of the slave during Δt. It can be concluded that the operator of the master has to be in a low speed to achieve a high precision.

*2) The Relationship between Linearized Model Error and Moving Direction*

Only tracking error of the line has been taken into account in discussing the possible error of the linearized model. The experimental method is described as follows: starting from the initial point, the tip of the slave moves equivalent distances along X, Y and Z. directions. The accumulated errors in each direction are compared. The sensitive error direction of the linearized model can be determined from this comparison. As shown in Fig. 11, the maximal error direction is along Z axes when the master-slave operation is performed.

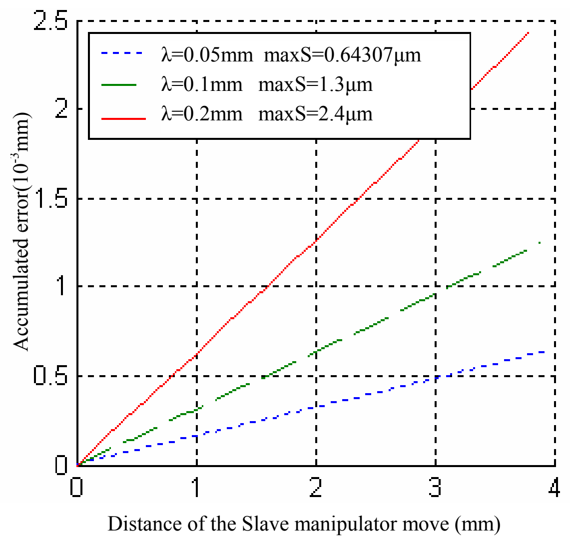

Fig.10 Track error in different precision

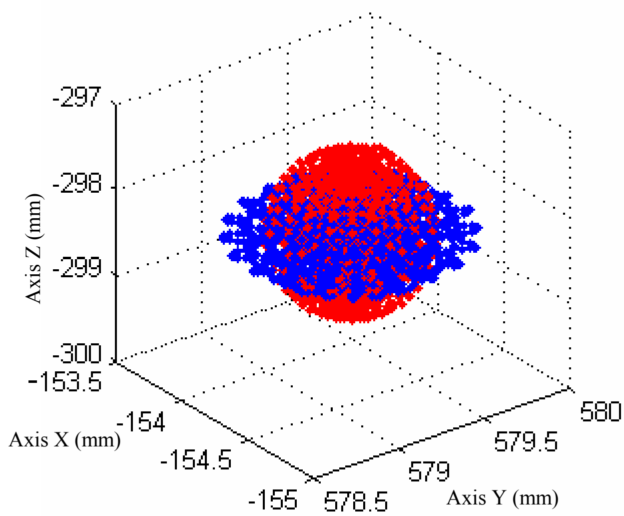

Fig.11 Sensitive direction of error

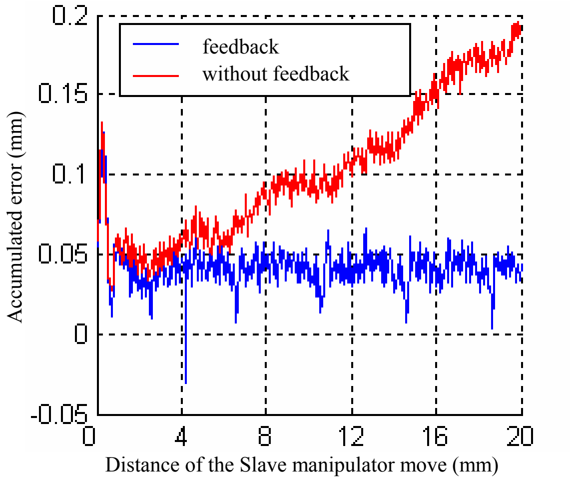


Fig.12 Compare original to improved linearized model

*3) Improvement of the Slave Linearized Model and Experimental Verification*

To reduce the accumulated errors caused by the linearized model, joint position errors are tested and fed back to the controller. This method has been verified by letting the tip of the slave move 100mm along Y axis with 0.2mm each step. As can be seen from Fig.12, the improved model greatly reduces the accumulated errors caused by the linearized model.

## VI. Controller and Multi-view Image System

### *A. Overview of the Control System*

Based on the PC, MicroHand control system has open system architecture. This control system makes full use of the various software resources in Windows and many kinds of PC communication interfaces, possesses Image collection and display, and force feedback function. The entire controlling process also involves force feedback and image collection and display, and function. The hard structures of the control system are shown in Fig.13, in which the PCI card is the product of National Instrument Company with Flexmotion-7344 Motion controller, IMAQ-1411 image collection, and DAQ-6024E data acquire. Panasonic AC servo systems are applied to drive the position joints. Step motor AM1020 and AM1020 from Arsape are used to drive the posture joints.

### *B. Multi-View Image System*

When a conventional surgical microscope is used in the robotic system, the operator of the master manipulators can only have two-dimension images on the screen. Due to lack of the information in depth, it would be difficult for the doctor to do micro-surgical operations (e.g., suturing). Based on a medical binocular microscope (XTS-6A), multi-view image systems are designed, as shown in Fig. 14. The system includes: 1) the primary image of XTS-6A surgical microscope, which can be transferred onto the screen in front of the operator by CCD No.I. The images can be magnified about 10 to 25 times. This enables the operator to implement long-distance modulation by a feet switch; 2) CCD No.II angled 40 degrees with the primary microscope on the arc orbit, providing 20-times magnified information in depth; 3) the image of the whole view provided by CCD No.III solves the problem of view reduction through increasing microscope magnification, benefits large-scale traction movement, and provides the information about surgical environment.

## VII. Animal Experiments

Microhand executed suturing experiments on a rabbit's 3mm-in-diameter neck artery and an artery in the leg of 1mm in diameter. The sequence of the micro-surgical operation is as follows:

At first, slicing off the cutis of surgical place (as shown in Fig. 15a);

Secondly, cutting blood vessels (as shown in Fig. 15b);

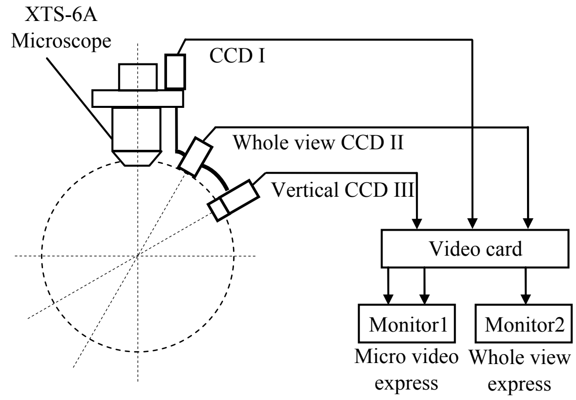


Fig.14 Image system of MicroHand

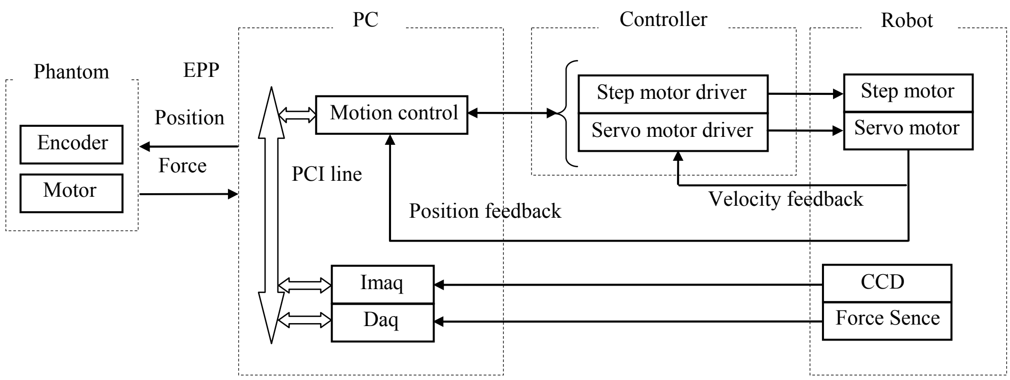


Fig.13 Control system construction scheme

Thirdly, peeling off artery ectoblast (as shown in Fig. 15c);

At last, suturing the blood vessel in 6 locations (as shown in Fig.15d) and knotting 2 times for one knot (as shown in Fig.15e).

It took about 40 minutes to complete this operation. Because of the 3-dimension force feeling, Microhand system can prevent tissues or vessel from being damaged during the operation. This animal experiment validates the Microhand system.

## VIII. CONCLUSIONS

A micro-surgery robotic system with force feedback has been developed. The validity of the system have been proved by animal experiments on the vas suturing for a rabbit's neck artery (3mm in diameter) and its leg artery (1mm in diameter).

## ACKNOWLEDGMENT

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Fig.15a

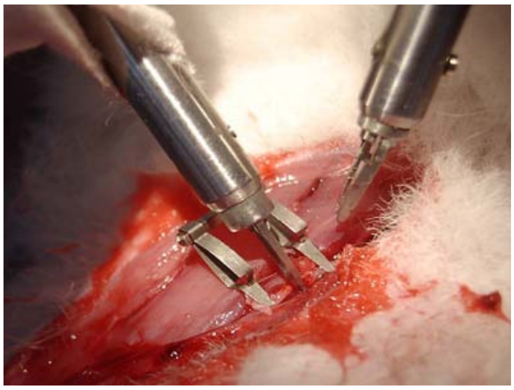

Fig.15b

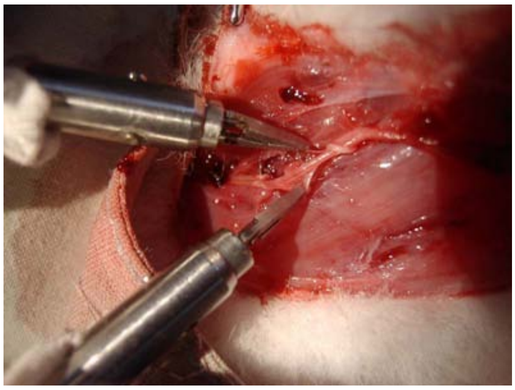

Fig.15c

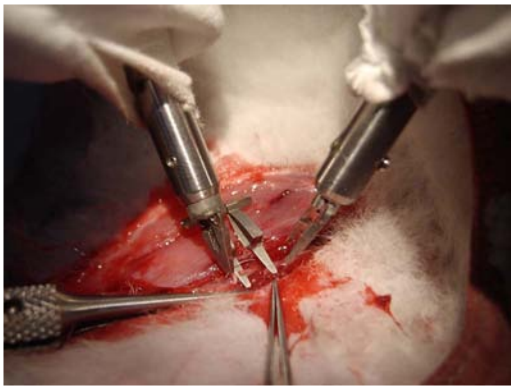

Fig.15d

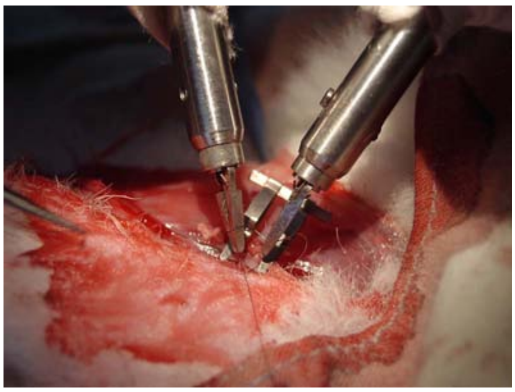

Fig.15e

Fig.15 Animal experiments of MicroHand system