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Mechanism study for Microsurgical Robotic System that can induce Multisensory Illusion

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In recent years, robotic technology has been introduced in surgery in the form of master slave system and its applicable surgical area is widely spreading. Minimally invasive surgery and microsurgery are the representing applications of the robotic surgery that the surgeon performs the dexterous and fine operations in the deep or narrow surgical area in micro-scale. The intuitiveness is thus highly desirable to perform the highly elaborated surgical tasks such as suturing for surgical master slave systems. To increase the operability, time-delay of system response, haptic feedback and eye-hand coordination issues have mainly been discussed in the field of robotics. In addition to these approaches, we propose a surgical robotic system that induces multisensory illusion. In our previous study, we reported that the robotic instruments enhances the multisensory illusion. In this paper, we determine the requirements for inducing the multisensory illusion on a multi-DOF master slave system and the first stage of prototype implementation based on the given requirements is described.

Keywords: Multisensory illusion; Surgical robot; Microsurgery.

1. Introduction

In recent years, robotic technology has been introduced in surgery in the form of Master Slave System (MSS), and its applicable surgical area is widely spreading (e.g. da Vinci, Intuitive Surgical Inc., US [1]). Minimally invasive surgery and microsurgery are the representing applications of robotic surgery that the surgeon performs the dexterous and fine operations in the deep or narrow surgical area in micro-scale. The intuitiveness is thus highly desirable to perform highly elaborated surgical

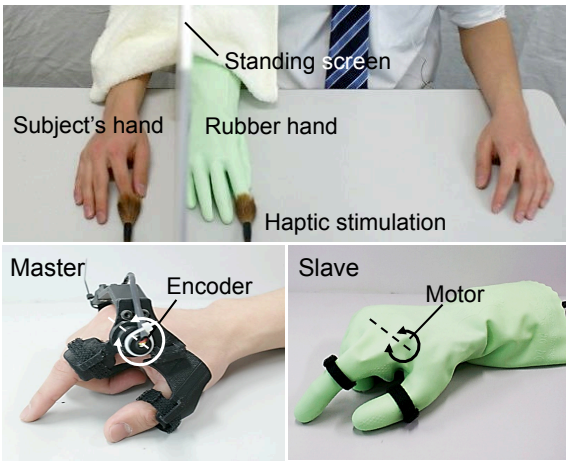

Fig. 1. The upper panel shows the commonly performed Rubber Hand Illusion. The lower panels show the 1 DOF robotic rubber hand master slave system from our previous study.

tasks such as suturing for surgical MSS. To increase the operability, time-delay of system response, haptic feedback and eye-hand coordination issues have mainly been discussed [2-8]. In addition to these approaches, we propose to introduce the multisensory illusion into surgical MSS.

2. Multisensory illusion and its requirements for robotic system

The Rubber Hand Illusion (RHI) is a well known multisensory illusion reported by Botovinick et al. [9]. The upper panel of Fig.1 shows the general setup of RHI. In general RHI, the subject is seated with his/her right arm resting on a table. A standing screen is placed beside the right arm to hide it from the subject's view and a rubber hand is placed on the table directly in front of the subject. Then, tactile stimulation is given to the subject's hidden hand and the rubber hand by stroking paintbrushes in synchronizing timing and position. After the stimulation, the subject feels as if the rubber hand becomes his/her hand. We have then introduced a 1 DOF MSS into the RHI experimental environment to investigate whether the body-image is transferable within the master slave motion on the RHI setup. The lower panels of Fig.1 show the 1 Degree Of Freedom (DOF) robotic RHI master slave system that we have presented in our previous study [10]. The robotic system has allowed us to perform active motions such as a table tapping task within the configurable artificial time-delay. Note that no actuator has implemented on the master device, however, the table tapping sensation is directly perceived by the subject, because his/her finger tip is exposed against the table surface. The results showed the robotic instruments significantly enhances the multisensory illusion. The detail of the experiments are described in the authors' previous paper [10]. From the

experimental results, we determine the following requirements to effectively induce the illusion on a multi-DOF MSS.

- As it has been shown in the previously presented papers, eye-hand coordination is significantly correlated to the level of multisensory illusion. The MSS thus should be designed considering the optimal alignment that realizes a well configured eye-hand coordination.
- From the experiment that the artificial time-delay has been inserted between the master and the slave, over 50 ms of time-delay has significantly deteriorated the multisensory illusion. It is thus necessary to implement the MSS within a time-delay less than 50 ms to effectively induce the multisensory illusion.
- Level of the illusion index has been significantly deteriorated by the mechanical constraint that was used for fixing the subject's fingers to the master device (Velcro straps). Contrary, Velcro straps on the tip of slave device have increased the illusion index, supposedly due to the resemblance that the subjects perceived from the visual and haptic (such as friction) stimuli as if the stimuli was given from that of the master device.
  From these facts, the master device has to be implemented to allow the user's motion with minimum constraints, in addition, the visual and haptic resemblance between the master and slave should be taken into account the device design.
- Appearance of general surgical robots do not resemble to human body (e.g. tweezers or forceps do not alike a human hand). However, our preliminary experiments showed that the multisensory illusion could be induced from the human hand to the objects in different shapes, such as scissors. It was also shown that the illusion can be enhanced by making the hand posture closer to the object (such as making a V sign for scissors). This shows the hand posture significantly related to the level of multisensory illusion.

Based on these requirements, we developed a multi-DOF master slave system for microsurgery that allows to effectively induce the multisensory illusion for further intuitiveness. This study is thus the first attempt to explicitly introduce the multisensory illusion in MSS. It should be noted that it remains still unclear whether the multisensory illusion contributes to the improvement of intuitiveness and operability in MSS. Therefore, the aim of the study is to develop a MSS based on the given requirements to investigate the effectiveness of multisensory illusion in MSS. The requirements described above let us explore the investigation of new mechanisms. In this paper, we introduce a first stage of prototype in describing newly developed mechanisms to fulfill these requirements.

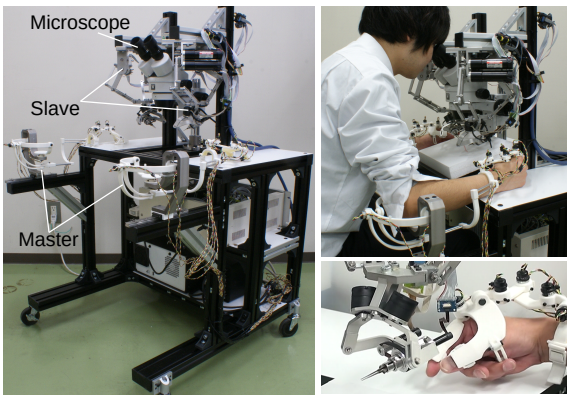

Fig. 2. The figure shows the developed microsurgical master slave system. The left panel shows the overview of the system, and the right panels show the closeup pictures with an operator.

3. Multisensory Illusion inducible Microsurgical Master Slave System

Based on the requirements described in the previous section, we developed MSS for microsurgery that is capable of suturing the blood vessels and nerves. Fig.2 shows the overview of the developed system. The system let the user to manipulate the slave robot precisely without the hand tremor. The mechanical setup has been designed in taking into account the eye-hand coordination based on the general RHI setup. An optical microscope is placed at the center of the system, and the slave arms are placed by the both sides of the microscope to perform the operation. The user places the both hands at the side of the slave device in wearing the master device. The master device let the user perform the motion freely regarding the elbow, wrist and grasping in resting his/her elbow on the armrest. Both master and slave have 7 DOF (3 translational DOF, 3 rotational DOF and 1 grasping DOF) at each arm to perform the operation. The user manipulates the system while viewing the microscopic image. Note that the time-delay due to the image processing does not occur in the system, because the user directly look into the optic microscope. In this section, the newly developed mechanisms for the master and slave are described.

3.1. *Master*

General master devices are commonly grounded joy-stick type controller that allows the system measuring the position and posture of the end-effector grabbed by the user. However, the master device in this study is required to be wearable and capable of measuring the position and posture of the user's hand without preventing the body movement in order to effectively induce the multisensory illusion. Therefore, the developed master was implemented as an exoskeleton device that can be worn by the user as depicted in Fig.3. The master can be attached to the user's body by

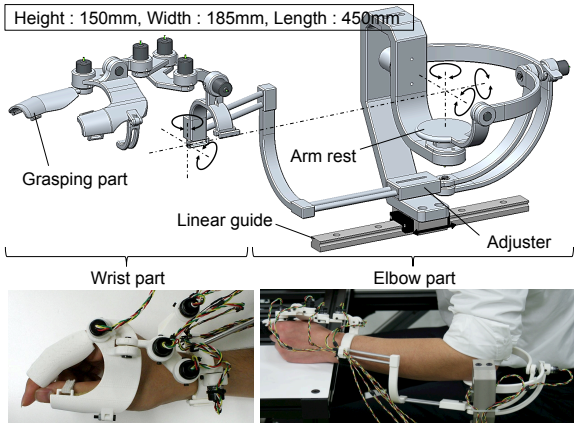

Fig. 3. Master device has 7 DOF with 3 DOF rotations and 1 DOF translation at elbow, 2 DOF rotations at wrist and 1 DOF grasping at the fingers.

three Velcro straps at the fingers and the wrist. The user places his/her elbow at the armrest, then he/she can freely move the forearm and the motion is measurable at 7 DOF. Developed master consists of the elbow, wrist and grasping parts.

3.1.1. *Elbow part*

The elbow part was implemented using six bar spherical parallel mechanism that has 3 rotational DOF. The spherical parallel mechanism realizes a Remote Center of Motion (RCM) at the user's elbow joint that is placed at the armrest, thus the user can move the 3 DOF elbow joint freely, while these 3 DOF motion angles are measured by the optical encoders attached on the mechanism. In addition, the elbow part is equipped with 1 translational DOF by a linear guide that enables the user's translational elbow motion back and forth along with the linear guide. The linear displacement is measured by a liner scale fixed along the linear guide within the accuracy of 0.1 mm.

3.1.2. *Wrist part*

Human wrist joint is well known that its joint center does not stay at the same point while its bending motion. The master was thus designed with a 4 DOF redundant serial mechanical chain for 2 DOF wrist bending motion to compensate the displacement of the user's wrist joint center. From our preliminary motion tests, the redundant mechanism largely contributed to the smooth motion input at the wrist by the user.

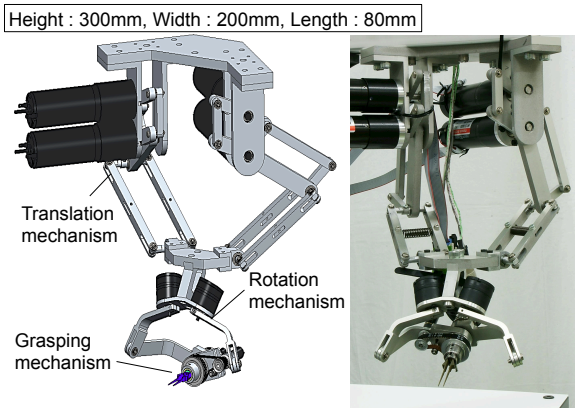

Fig. 4. The slave has 7 DOF that consists of translational (3 DOF), rotational (3 DOF) and grasping part (1 DOF). The compact implementation enables the mechanism to be placed at the both sides of the microscope.

3.1.3. *Grasping part*

At the tip of the master, the grasping part was implemented that enables the measurement of the rotation angle of the user's MP joint at the index finger. The mechanism was designed based on that of the 1 DOF robotic instruments for RHI we previously developed.

The master was fabricated by ABS rein using 3D printer (uPrint SE Plus, Stratasys Ltd., US), except the metal bearings at each rotary joint for the lightweight implementation. The approximate size of the master is 150 mm in height, 185 mm in width, 450 mm in length and 129.3 g in wight for each arm. The master is equipped with an adjuster that allows the device to be worn by users in different arm sizes. All the optical encoders are equipped with MEH-9-1000PST16C (Microtech Laboratory Inc., Japan) that the resolution is 1000 pulse/rotation multiplied 16 times. Thus the motion angle of user is measurable at 0.0225 deg of resolution. And the linear motion of the elbow is measured by the linear scale MLS-12-600C-250 (Microtech Laboratory Inc., Japan) that the resolution is 0.1 mm. Note that the master is not equipped with any actuators for force feedback.

3.2. *Slave*

The slave is required to perform dexterous manipulations of tissues by the two arms that have 7 DOF (3 translational DOF, 3 rotational DOF and 1 grasping DOF) at each arm. In addition, the two arms are required to be placed across the microscope, and the user's arms are placed just side-by-side with the slave to provide a well configured eye-hand coordination. The size of the slave thus must be compact and should not prevent the user's motion. In addition, the time-delay is the key issue for the multisensory illusion and must be less than 50 ms. The slave device was

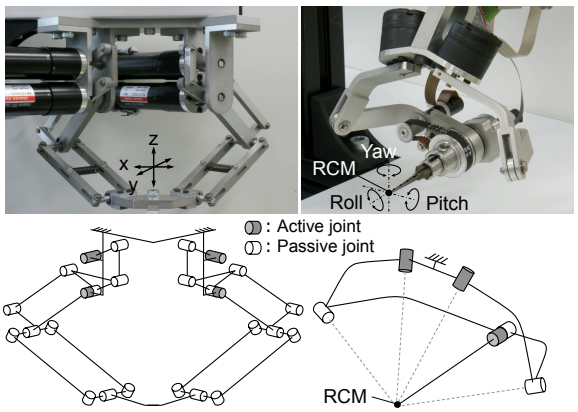

Fig. 5. The left panels show the translational mechanism that was developed based on the authors' previously presented mechanism. The right panels show the rotational mechanism that has a RCM at the tip of tweezers.

designed by taking account above issues as depicted in Fig.4. The developed slave consists of translation mechanism, rotation mechanism and grasping mechanism.

3.2.1. *Translation mechanism*

The translation mechanism is depicted at the left panels in Fig.5. The mechanism was developed by applying the 3 DOF redundant parallel mechanism DELTA-R that has been presented by the authors' previous work [11]. In general parallel mechanisms, all actuators are fixed at the base part, thus the mechanism inherently has the advantage on the high-speed motion that is one of the key issue to minimize the time-delay. DELTA-R is a redundant parallel mechanism actuated by the four motors for the 3 translational DOF. The advantage of DELTA-R is the wider range of working area, smaller foot print and improved force producibility compared to conventional 3 DOF translational parallel mechanisms. In addition, the DELTA-R can be placed one-sided thanks to the two-arm configuration thus can be effectively introduced to the application in this study. The prototype of the translation mechanism was implemented using four DC servo motors (RE30 with the gear head GP32A and the optical encoder MR Type L, Maxon Motor AG, Switzerland). The reduction gear ratio is 1/14 and the resolution of optical encoder is 512 ppr, thus the resolution of position control in taking into account the kinematic model is: 0.050 mm for X axis, 0.029 mm for Y axis and 0.015 mm for Z axis (at the center of the working area). The mechanical structure of the translation mechanism was fabricated by aluminum alloy (A5052). The weight of the mechanism is 560.0 g. Note that the weight of the motors are not including in the weight, because the base part of the mechanism is fixed thus does not influence to the mechanism's characteristics. This lightweight design enables us to reduce the effect of inertial

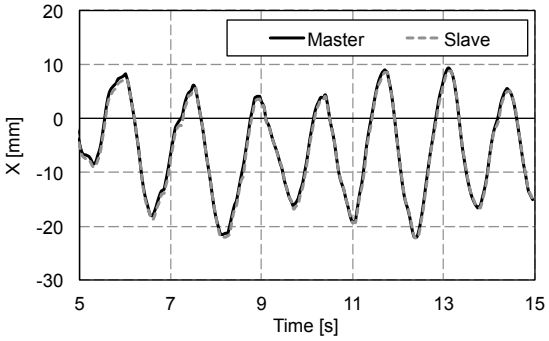

Fig. 6. The figure shows the result of a preliminary motion test conducted for translational motion on X axis. The test showed 13 ms of the time-delay and the maximum position error of 0.15 mm.

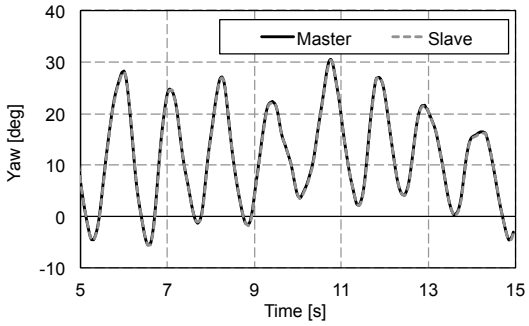

Fig. 7. The figure shows the result of a preliminary motion test conducted for rotational motion on yaw axis. The test showed 17 ms of the time-delay and the maximum position error of 0.41 deg.

force while manipulation. It is assumed that the position error between the master and the slave would largely influence the level of multisensory illusion. Fig.6 shows the representative result of the preliminary motions tests regarding X axis. Note that the tests were conducted at the input speed of approximately 20 mm/s that was configured in taking into account the maximum speed in general microsurgical tasks.

The preliminary tests on the prototype reveal that the mechanism has 13 ms of time-delay and the maximum position error was 0.15 mm. Note that the error described here is mainly due to the time-delay thus is observed at the peaks (when the user switch the direction of motion). Therefore, this error can be largely decreased while the fine manipulation that the user moves the robot relatively slower, because the resolution of the mechanism is significantly higher. From the results, the translation mechanism showed a sufficient performance for this study.

3.2.2. *Rotation mechanism*

The rotation mechanism is depicted at the right panels in Fig.5. The rotation mechanism was implemented based on Five-Bar-Linkage parallel mechanism that has been presented by Ouerfelli et al. [12]. Five-Bar-Linkage is spherical parallel mechanism that has 2 rotational DOF of pitch and yaw that the RCM is located at the center of the spherical links. In the developed rotation mechanism, we added 1 rotational DOF for the rotation along the tweezers' long axis. The pitch and yaw axes are actuated by two flat DC servo motors (024SR, Faulhaber GmbH, Germany). The motor is equipped with the gear head with 1/112 reduction gear ratio and the optical encoder with 16 ppr. The roll axis is actuated by a DC servo motor (RE10, Maxon Motor AG, Switzerland) with the gear head GP10K (1/16 reduction gear ratio) and the optical encoder MR Type S (128 ppr). The mechanism thus realizes three rotational motions within a RCM located at the tip of tweezers. The resolusion of position control in taking into account the kinematic model is 0.073 deg for pitch and yaw axes, and 0.350 deg for roll axis. The mechanical structure of the rotation mechanism was fabricated by aluminum alloy (A5052) for a lightweight implementation. The weight of the mechanism is 248.6 g including the motors. The preliminary tests on the prototype showed that the mechanism has 15 ms of time-delay and the maximum position error was 0.25 deg regarding pitch and yaw axes. 17 ms of time-delay and 0.41 deg of the maximum position error was observed for roll axis. Fig.7 shows the representative result of the measurements regarding yaw axis. Note that the tests were conducted by at the speed of approximately 30 /deg that was configured from the maximum speed in general microsurgical tasks. Part of the motion error was caused by the mechanical play due to the fabrication process of mechanical links, and the improvement is currently on-going. The error also comes from the time-delay thus observed at the peaks (when the user switch the direction of motion). Therefore, this error can be largely decreased while the fine manipulation because the user move the robot relatively slower.

3.2.3. *Grasping mechanism*

The grasping mechanism is depicted in Fig.8. The grasping mechanism consists of the grasping part made of the elastic beam (SUS304) and the driving part actuated by a linear actuator (RE8, Maxon Motor AG, Switzerland). The motor is equipped with the gear head GP8S (1/16) and the optical encoder MR Type S (100 ppr). The grasping part enables the open and close motion of the tip of tweezers in deforming the elastic beam. The mechanism is thus inherently low backlash and capable of the stable grasping. In addition, the grasping mechanism largely contribute to reduce the mechanism complexity and thus decrease the number of mechanical parts, that is significant for the sterilization process. In practical use in microsurgery, the whole slave robot should be draped by a sterile cover. The grasping part is only the part exposed to the surgical area and can be easily detached from the robot and sterilized using a conventional sterilization method such as autoclave. The size of the grasping

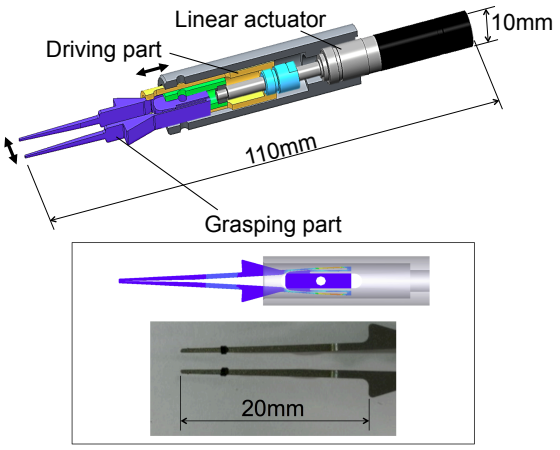

Fig. 8. Grasping mechanism was implemented by a linear actuator and elastic beam that performs the tweezers' open and close motion.

part was implemented based on conventional tweezers for microsurgery, and the size of the tip is 20 mm in length and 0.5 mm in thickness. The stroke of the grasping motion is 5 mm and the resolution of position control in taking into account the motor specification and the kinematic model is 0.0003125 mm. From the FEM analysis shown at the lower panel in the Fig.8, the strain is distributed widely at the elastic beam while the grasping motion. The observed maximum strain was 0.15 % that is far below the yield point. It was shown that the artificial vessels and suturing needles are stably grasped by the mechanism in a preliminary motion test. The feasibility of the grasping mechanism was thus positively shown.

4. Preliminary evaluation

To test the practical performance of the developed MSS, we conducted a preliminary evaluation experiment. The controller for the developed microsurgical MSS was implemented by using MATLAB xPC target in 1 kHz control loop. Note that the controller was equipped with a low pass filter (cutoff frequency is 50 Hz) for the master motion input in order to reduce the hand tremor from the user. In the experiment, a novice subject (non-MD) was instructed to performed a suturing task on a artificial vessel (diameter of 1.5 mm). The subject was seated in front of the system and wore the master device to manipulate the slave as shown in the Fig.2. Fig.9 shows the image sequence taken during the suturing task. The subject successfully performed the suturing task without having the difficulty compared with the conventional suturing task using microscope. It was also shown that the developed system was capable of a series of microsurgical procedures such as a general tissue handling.

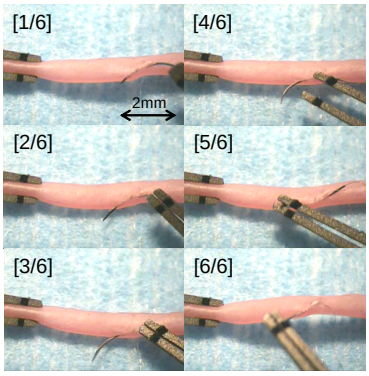

Fig. 9. Image sequence of suturing task paformed by the prototype. The diameter of the phantom vessel is 1.5 mm.

5. Conclusion

In this study, we developed a microsurgical MSS that is capable of inducing the multisensory illusion. To develop the robotic system, we first investigated the requirements based on our previous study. To adapt these requirements to a multi-DOF MSS, we developed new mechanisms using parallel mechanism. The developed microsurgical MSS showed the practical utility in micro suturing tasks. We are currently investigating the effect of multisensory illusion while the surgical tasks through the psychophysical experiments configured based on the previously presented studies regarding the multisensory illusion [13-20]. The final goal of this study is to develop a MSS that the user can manipulate the slave ultimately intuitive - as a part of his/her body. The presented robotic system will be used to assess the effect of multisensory illusion and will be further improved for the higher level of the multisensory illusion.

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