Motion Control of a Master-Slave Minimally Invasive Surgical Robot Based on the Hand-Eye-Coordination

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Abstract:
During robot-assisted minimally invasive surgery, the surgeon controls the surgical instruments insides the patient's body through teleoperation technology. For the surgeon, the endoscope and the surgical instruments insides the patient's body are just like his/her own "eyes" and "hands" extended in space. Hence the motion alignment between the master control handles and the end effectors of the associated slave manipulators should be carefully designed so as to maximally coordinate the "hands" and the eyes of the surgeon, which can give the surgeon the same feeling as carrying out an open surgery. However, for an optionally laid out master console, how to design the motion aligning strategy, which can realize "How You Move Is What You See", is still not answered in relative researches. In this paper, we will try to find an answer to this question.

1. Introduction

A master-slave minimally invasive surgical (MIS) robot usually consists of a master control console and several slave robot manipulators, on the end of which different surgical instruments could be mounted. During robot-assisted minimally invasive surgery, the surgeon only need to sit by the master console and perform different operation actions with the input handles. Then, the movement of their hands will be translated into more precise micro-movement of the surgical instruments mounted on the slave manipulators with the help of teleoperation technology. For the surgeon, the endoscope and those surgical instruments insides the patient's body are just like his/her own "eyes" and "hands" extended in space. Hence the translational and orientational relationship between the master control handles and the end effectors of the associated slave manipulators should be carefully designed so as to maximally ensure the hand-eye-coordination of the surgeon (to achieve the "How You Move Is What You See" effect), which can give the surgeon the feeling as carrying out an open surgery. G. Niemeyer et al. [2][3] from Intuitive Surgical Inc. have proposed a method to align the movement of the master and slave devices and have successfully applied it in the da-Vinci MIS robotic system. It has been proved to be very effective and adopted by many other MIS robotic systems[4][5]. However, the proposed method has some special requirements on the corresponding positions of the input handles relative to the viewer of the master console. For an optionally laid out master console (which means arbitrary corresponding positions of the input handles relative to the viewer), how to design the alignment between the master and slave devices' movement is not mentioned in their researches. And currently, there are few researches of MIS robot focusing on this area [6][7]. Hence, in this paper, we aim to find an answer to this question and propose a motion aligning method to match the master and slave devices' movement based on the principle of hand-eye-coordination for those MIS robots with an optionally laid out master console.

This paper is organized as follows. After the introduction, our research platform will be introduced at first, which consists of an optionally laid out master console and some virtual slave manipulators. Then an abstract model of the tele-manipulation process using our master console will be established and analyzed. Based on the model obtained and the "hand" (surgical instrument)-eye -coordination principle, a motion aligning method will be designed and implemented in our virtual MIS robot system to match the master and slave devices's movement, so as to offer the user a nature and intuitive control experience. To examine the effectiveness of the herein proposed motion aligning method, some evaluation experiments were designed and conducted and the results will be discussed. Finally, conclusions will be drawn and future work will also be given in the last section of this paper.

2. Our research platform

As shown in Fig.1, our research platform consists of a 7-DOF haptic device Omega7 (Force Dimension Inc.) as the input handle and a virtual slave surgical robotic system in the OpenHRP3 [8] (an open source simulation environment). The virtual slave robotic system includes three slave manipulators: two of them are surgical instrument carrying manipulator and the third one is an endoscope holding manipulator. Based on the image provided by the virtual endoscope, we can obtain the real-time condition of the surgical autonomy area and then utilize the Omega7 to control the virtual slave manipulators to perform different surgical actions.

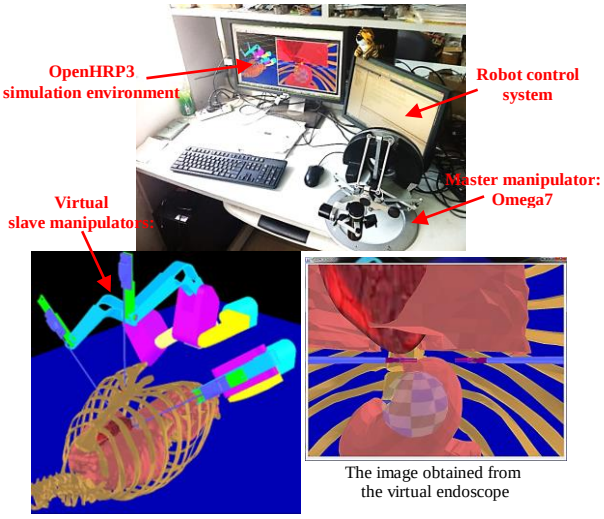

Fig. 1. Our research platform: a 7-DOF haptic device Omega7 and a virtual slave robotic system (only active joints are shown here) in the OpenHRP3 simulation environment.

2.1 The master device

The master control device Omega7 has totally seven joints: three joints (Delta mechanism) for the spatial translation of the end effector, three wrist joints (mutually orthogonal) for the rotation and the last one for the pinch action of the fingers. The structure diagram of Omega7 is depicted in Fig.2. As we can see, the translational and rotational movement of the end effector are completely decoupled. Hence, its forward and inverse kinematics (FK, IK) analytic solution can be easily obtained [9]. By periodically computing the position and orientation of the master device's end effector, the robot control system can record every movement of the surgeon's hand and then command the slave manipulator to reproduce every surgical action inputted by the surgeon.

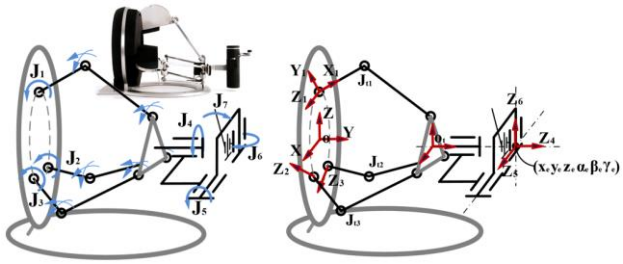

Fig. 2. The structure diagram of the master control device Omega7.

2.2 The slave devices

As mentioned before, our virtual MIS robotic system has three slave robotic manipulators in total, two of them are surgical instrument carrying manipulator, and the third one is an endoscope holding manipulator. The difference between them is that, the surgical manipulator has totally eleven joints, four passive setup joints and seven active joints while the endoscope holding manipulator has only seven joints in all, four passive setup joints and three active joints. The structure diagram of two types of manipulator are depicted in Fig.3. For those serial manipulators, the FK problem is relatively simple while its IK problem is a little complicated. Since all passive setup joints will be deadlocked after the setup of the MIS robot and will not move during the surgery, only active joints need to be taken into consideration during the IK solving process. However, for the 7-DOF surgical manipulator, it is a little hard to get the analytic solutions to its IK problem since it doesn't meet the Pieper condition [10][11]. And iteration methods are also not applicable here since they will cost too much time and computing resource, which is not expected in a real-time robotic system. Thus, we need to find a new real-time solving method for the IK problem. As we can see from Fig.3, three wrist joints are very close to each other and also to the end effector, thus their rotation will only have limited influence on the end effector's position. So, the IK problem can be solved in two steps: Step 1, ignore the influence of three wrist joints' rotation, we can easily obtain the angles of the former three active joints according to the end effector's current position; Step 2, based on the result of step 1 and the current orientation of the end effector, angles of three wrist joints could then be calculated. In this way, we can easily get the analytic IK solutions of all joints. In addition, error compensation is conducted in each control cycle so as to eliminate the position error caused by the herein proposed two-steps IK solving approximate algorithm.

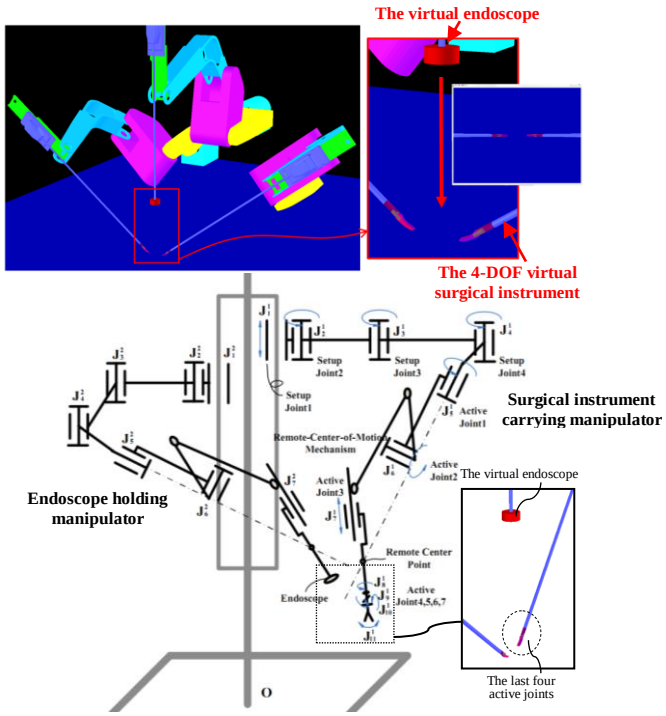

Fig. 3. The structure diagram of the slave robotic manipulators.

3. Master-slave motion alignment based on the principle of hand-eye-coordination

After obtaining the FK and IK solution of the surgical robot, now we need to align the movement of the master and slave device's end effector. Before that, we will introduce the hand-eye-coordination ability of human being first.

3.1 The principle of hand-eye-coordination

Hand–eye coordination ability [12], which is an important component of human's bodily-kinesthetic intelligence, mainly means the ability of the vision system to coordinate the information received through the eyes to control, guide, and direct the hands in the accomplishment of a given task, such as catching a ball or handwriting, as shown in Fig.4. During the task, man can adjust the direction of the hands' movement and the strength of the operating force in real time according to the visual information and the proprioception, so as to accomplish very delicate operation actions. One's hand–eye coordination ability has already been developed and formed in his/her growing process. It is a basic mechanism of daily activities, people who lack this ability will not be able to complete even the simplest operation such as grasping an object.

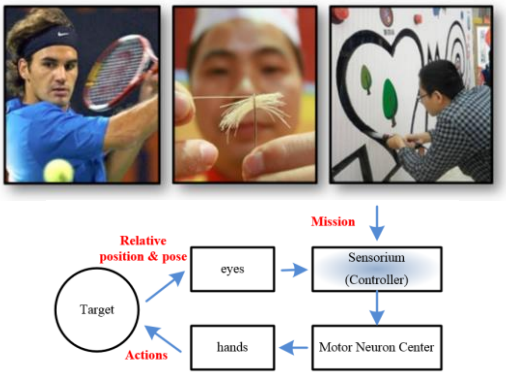

Fig. 4. The hand–eye coordination ability of human being.

The hand–eye coordination ability mentioned above mainly refers to the coordination of the human eyes and human hands. However, with the rapid development of science and technology, an increasing number of tasks require that people control a manipulator to complete them. In this case, the concept of hand-eye coordination should be extended to the coordination of all mechanical manipulators and the human eyes. The manipulator is just like human's another "hand" extended in space, but the difference is that the manipulator's reference coordinate system is normally not consistent with the user's intuitionistic reference coordinate system, as shown in the left figure of Fig.5. Hence, for the user, the operation of the manipulator is not so natural and intuitive. Lots of training is needed so as to establish a new coordination relationship between the new "hand" and the eyes, then they can master the movement of the manipulator.

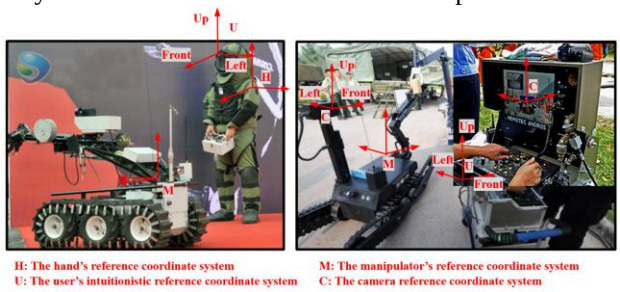

Fig. 5. A new hand–eye coordination relationship between the robotic manipulator and human's eyes.

In some cases, a camera will be mounted on the robot to help the user with the manipulation, as shown in the right figure of Fig.5. The camera reference coordinate system could always be consistent with the manipulator's reference coordinate system and the user's intuitionistic reference coordinate system, thus for the user, the manipulator would always move in the same direction as he/she wishes. In this way, the manipulation also appears to be more natural and intuitive.

Based on the above analysis, we can infer a requirement for the realization of intuitive teleoperation of a master-slave MIS robot, we named it **the principle of hand-eye-coordination**, which is as follows: **In the view of the operator (in the operator's intuitionistic reference coordinate system), the translational and rotational movement of the slave manipulator's end effector should always be consistent with the movement of the master manipulator's end effector.** Based on this principle, in the following part, we will introduce a master-slave spatial motion aligning method for the MIS robot with an optionally laid out master console. After that, we will also design an evaluating experiment to verify the effectiveness of the herein proposed hand-eye-coordination principle.

3.2 Master-slave motion alignment based on the principle of hand-eye-coordination

For a master console with an optional layout, the tele-manipulation process with it can be described with an abstract model as illustrated in Fig.6. For different layouts, the setup angle of the display screen θ_{disp} and the master manipulators θ_{m-c} could be various. And in Fig.6, some important reference coordinate systems have also been depicted, they are: the user's intuitionistic reference coordinate system $(O_{user}X_{user}Y_{user}Z_{user})$; the display device's reference coordinate system $(O_{disp}X_{disp}Y_{disp}Z_{disp})$; the endoscope reference coordinate system $(O_{cam}X_{cam}Y_{cam}Z_{cam})$; the reference coordinate system of the master device's end effector $(O_{m-e}X_{m-e}Y_{m-e}Z_{m-e})$ and base $(O_{m-b}X_{m-b}Y_{m-b}Z_{m-b})$, the slave device's end effector $(O_{s-e}X_{s-e}Y_{s-e}Z_{s-e})$ and base $(O_{s-b}X_{s-b}Y_{s-b}Z_{s-b})$. According to the hand-eye-coordination principle, in the operator's eyes $(O_{user}X_{user}Y_{user}Z_{user})$, the translational and rotational movement of the slave manipulator's end effector's virtual image $(O_{s-e}X_{s-e}Y_{s-e}Z_{s-e})$ should always be consistent with the movement of the master manipulator's end effector $(O_{m-e}X_{m-e}Y_{m-e}Z_{m-e})$.

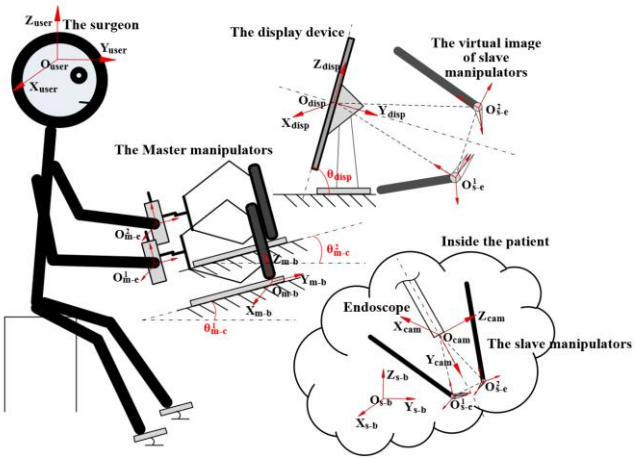

Fig. 6. An abstract model of the surgical tele-manipualtion process using an optionally laid out master console.

Take the right hand as an example, as shown in Fig.7, when the surgeon inputs a translational action, by solving the forward kinematic problem of the master manipulator, we can obtain a space vector $\Delta\vec{d}^1_{mb}\left(\Delta d^1_{x-mb},\Delta d^1_{y-mb},\Delta d^1_{z-mb}\right)$ which can describe the movement of the end effector in the master manipulator's base coordinate system $(O_{m-b}X_{m-b}Y_{m-b}Z_{m-b})$. By applying a coordinate transformation, we can get a new vector $\Delta\vec{d}^1_{mu}\left(\Delta d^1_{x-mu},\Delta d^1_{y-mu},\Delta d^1_{z-mu}\right)$ that describes the same movement in the user's intuitionistic reference frame $(O_{user}X_{user}Y_{user}Z_{user})$, and $\Delta\vec{d}^1_{mu}=\Delta\vec{d}^1_{mb}*T_{b-u}(\theta^1_{m-c})$, in which, $T_{b-u}(\theta^1_{m-c})$ is a coordinate transformation matrix. Then according to the principle of hand-eye-coordination, the translational movement of the slave manipulator's virtual image in the user's intuitionistic reference frame $\Delta\vec{d}^1_{su}\left(\Delta d^1_{x-su},\Delta d^1_{y-su},\Delta d^1_{z-su}\right)$ should be consistent with that of the master manipulator $\Delta\vec{d}^1_{mu}$. Hence, we have $\Delta\vec{d}^1_{su}=k*\Delta\vec{d}^1_{mu}$, k is a motion scaling factor. Then by applying another coordinate transformation, we can obtain the translational movement of the slave manipulator's virtual image in the display device's reference frame $\Delta\vec{d}^1_{sd}\left(\Delta d^1_{x-sd},\Delta d^1_{y-sd},\Delta d^1_{z-sd}\right)$ $=\Delta\vec{d}^1_{su}*T_{u-d}(\theta_{disp})$, in which $T_{u-d}(\theta_{disp})$ is also a coordinate transformation matrix. And according to the imaging principle, the movement of the real slave manipulator in the endoscope's reference frame $\Delta\vec{d}^1_{sc}\left(\Delta d^1_{x-sc},\Delta d^1_{y-sc},\Delta d^1_{z-sc}\right)$ should be equal to the movement of the slave manipulator's virtual image in the display device's reference frame $\Delta\vec{d}^1_{sd}$, so we get $\Delta\vec{d}^1_{sc}=\Delta\vec{d}^1_{sd}$. Further, based on the position and orientation of the endoscope, we can obtain the movement of the real slave manipulator $\Delta\vec{d}^1_{sb}$ in its base coordinate system. In this way, we have established an alignment between the translational movements ($\Delta\vec{d}^1_{mb}$ and $\Delta\vec{d}^1_{sb}$) of the master and the slave manipulator's end effector in their own reference frame.

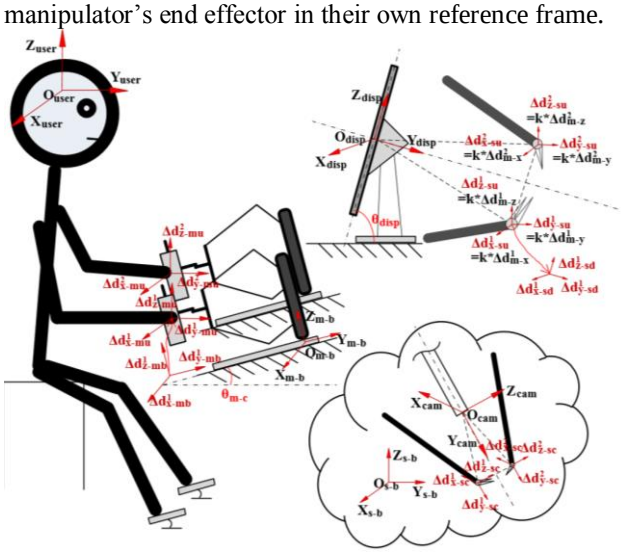

Fig. 7. The master-slave translational motion aligning procedure.

For the alignment of the rotational movement, the analysis is similar as before. As shown in Fig.8, first we can get the rotational motion vector of the master manipulator's end effector in its base reference frame by solving its forward kinematics. Then by applying a coordinate transformation, we can a new vector that describes the same rotational movement in the user's intuitionistic reference frame. According to the principle of hand-eye-coordination, in the user's intuitionistic reference frame, the rotational movement of the slave manipulator's end effector's virtual image should also be consistent with the rotational movement of the master manipulator's end effector. Based on this, we can get the rotational motion vector of the slave manipulator's end effector's virtual image. Similar as before, we can then get the rotational movement of the slave manipulator's end effector's virtual image in the display device's reference frame, the rotational motion vector of the real slave manipulator's end effector in the endoscope's reference frame and finally the rotational movement of the slave manipulator's end effector in its base coordinate system.

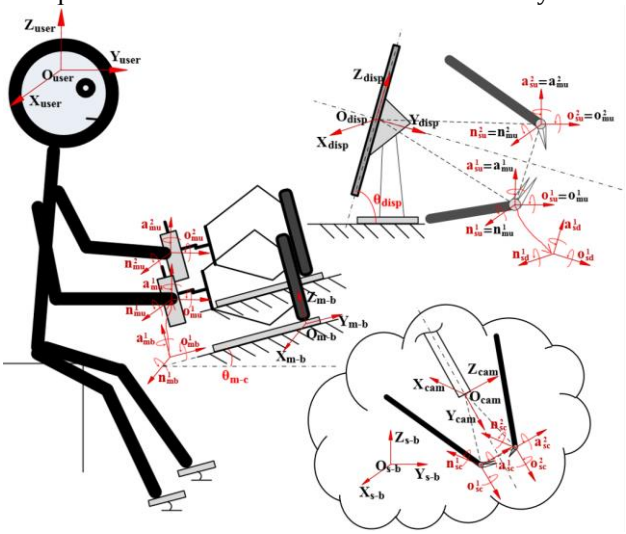

Fig. 8. The master-slave rotational motion aligning procedure.

So, we have established an alignment between the translational and rotational movements of the master and the slave manipulator's end effector in their own reference frame. Next, we will implemented this alignment in our virtual MIS robot and conduct an evaluating experiment to verify the effectiveness of the herein proposed method.

4. Evaluating experiment and its result

Based on the motion aligning method introduced before, we can now intuitively manipulate the slave surgical manipulator and easily perform various kinds of operation actions, as shown in Fig.9. In the view of the operator, the translational and rotational movement of the slave manipulator's end effector will always be consistent with the movement of the master manipulator's end effector.

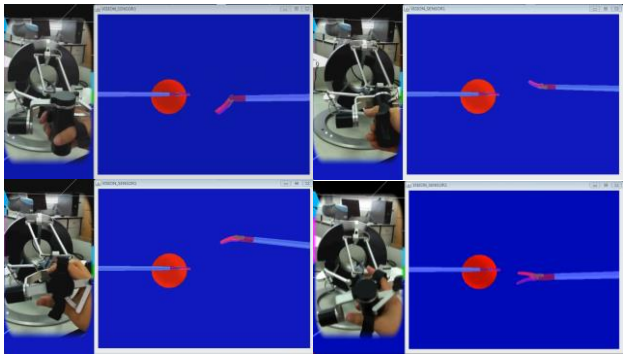

Fig. 9. Different kinds of operation actions can be easily and intuitively realized

To further verify the effectiveness of the proposed motion aligning method, we have also designed another evaluating experiment to evaluate the intuition of the manipulations using different motion aligning strategies. As shown in Fig. 10, in the workspace there are five intermediate targets (the green boxes, numbered from 1 to 5), one ultimate target (the red sphere, numbered 6) and some prohibited areas (those red boxes). During the experiment, the operator needs to manipulate the end effector to touch those targets in order. And any touch of the red boxes or wrong targets during the manipulation will incur a penalty, the operator will not be able to manipulate the end effector in 3s. The total time needed to finish the whole task will be noted and compared. Eleven volunteers have taken part in our evaluating experiment, each of them will complete the manipulation task for three times and the result is shown in Fig.11.

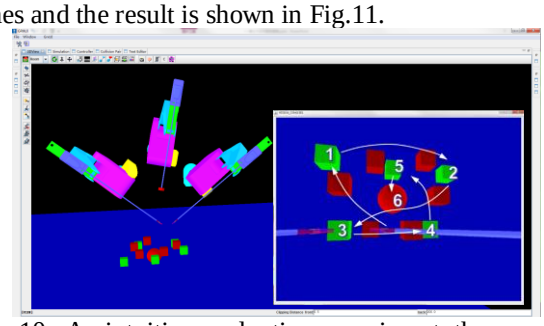

Fig. 10. An intuition evaluating experiment: the operator needs to manipulate the end effector to move from 1 to 6 in order and the consumed time will be noted and compared.

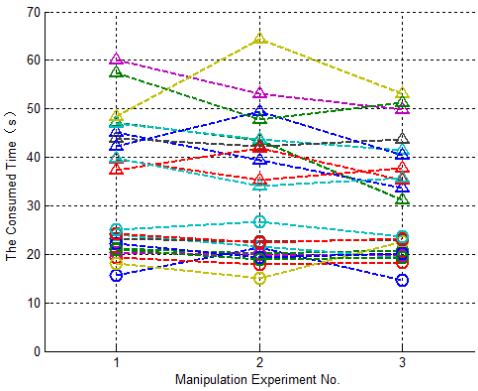

Fig. 10. The consumed time of each volunteer to finish the task using different motion aligning strategies.

The circle markers in Fig.11 indicates the consumed time of each volunteer when using the hand-eye-coordination principle based motion aligning method, while the triangle markers indicates the consumed time when using a simple motion aligning method (making the movement of the master and slave manipulator's end effector equal in the world coordinate system). As we can see, the volunteers can finish the manipulation task faster when using the herein proposed method (circle markers).

And Fig.11 illustrates the trajectories of the slave manipulator's end effector during two manipulations, in which different motion aligning strategy is implemented. We can see that, when using the herein proposed motion aligning method, the volunteers can finish the manipulation task more accurately and quickly.

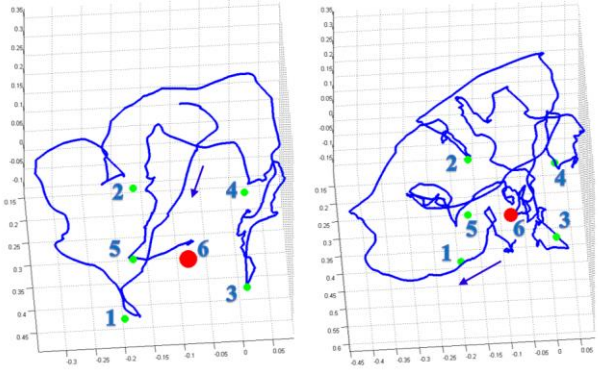

Fig. 11. The trajectories (marked in blue) of the surgical instrument during two manipulations: (left) the herein proposed motion aligning method is applied; (right) another simple and commonly used motion alignment strategy is implemented.

5. Conclusion and future work

In this paper, based on the principle of hand-eye-coordination, we have proposed a new master-slave motion aligning method for those MIS robots with an optionally laid out master console, which can maximally ensure the intuition of the surgical teleoperation. And the evaluating experiment result shows that using the herein proposed motion aligning strategy, the operator can finish different manipulation tasks more accurately and quickly. In the future, we will further test the herein proposed method in a real MIS robot system developed in our laboratory.

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