Workspace Mapping and Control of a Teleoperated Endoscopic Surgical Robot

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***Abstract*—This paper presents the experimental implementation of a teleoperated endoscopic surgical manipulator system that uses PHANTOM Omni haptic device as the master. The 4-DOF, 2-PUU_ 2-PUS, endoscopic surgical parallel manipulator design is carried out using screw theory and Parallel virtual chain methodology to have larger bending angles and workspace volume. The master and slave devices of the teleoperation system are dissimilar in their kinematics and workspace volumes. A workspace mapping technique is implemented based on Position with Modied Rate Control to navigate through the slave workspace without annoying the user. To control the motion of the slave robot, a PID controller is used. The experimental results show the feasibility of the teleoperation surgical system using the 4-DOF parallel manipulator. Also, they indicate the efficiency of the implemented mapping technique and the designed controller to span the slave workspace with high dexterity and good tracking which allows the surgeon to perform the operation with high accuracy.**

I. Introduction

Minimally Invasive Surgery (MIS) has become more and more applicable in the therapeutic uses in the current time. It is used to reduce trauma, infection and recovery time in hospitals as it uses small size incisions for inserting surgical tools inside patient body. Generally, the endoscopic manipulators which exist in clinical use can be classified into two main categories: flexible mechanism and rigid mechanism manipulators. Almost all of the existing commercial surgical systems are flexible mechanisms which transmit the mechanical motion via wires. There are two commercial systems that use flexible wire driven mechanism, the first one which is currently in clinical use is the da vinci system produced by Intuitive Surgical, Inc. [1]. The second one which has been in clinical use but is now discontinued is the Zeus system produced by computer motion, Inc. [2]. Despite that, the wire actuated type is widely used, it has a lot of defects such as difficulty in sterilization process in laparoscopic applications. Also, the wire may be ruptured during the operation and the surgeon needs to complete the surgery by himself.

The second category is rigid mechanism manipulators in which a mechanism is used to transmit the motion to the end-effector to perform the surgery. Recently, parallel mechanisms are actively involved in many medical applications due to their potential advantages compared to serial ones. These merits are payload capacity, structural stiffness and accurate precision. Robotic forceps manipulator has been developed by Ishii et al. [3]. This mechanism uses a new double screw drive mechanism but the fabrication accuracy needs improvement. An endoscopic manipulator that uses parallel mechanism has been developed by Rose. et al. [4], but the maximum bending angles for this manipulator are not equal in all directions due to the different design of the parallel chains. An endoscopic forceps manipulator has been presented by Yamashita et al. [5]. This manipulator has 3-DOFs; 2-DOFs for bending using multi-slider linkage mechanism and 1-DOF for the gripper. Problems were reported about accuracy and power consumption. An active forceps manipulator has introduced by Kobayashi et al. [6]. This manipulator has high rigidity, but the bending angle range can't exceed 50^o due to constraints in the design of the mechanism.

K. Ibrahim et al. proposed a 4-DOF parallel manipulator (2-PUU_2-PUS) where the feasibility of the design is proved by computer simulations. Also, The workspace of the bending mechanism is increased significantly and reached the limits of $\pm 90^o$ in all directions which is proved by computer simulations and analytically. The simulated control system for bending motion is presented. Finally, a real model of the 4-DOF parallel manipulator is manufactured from annealed stainless steel [7].

Rigid mechanisms driven manipulators are challenging because of the difficulty in controlling the end-effector motion with high dexterity. Also, the control of the master/slave configuration is challenging. The main goal of this paper is to present the implementation of overall teleoperation system practically using the new endoscopic parallel manipulator (2-PUU_2-PUS) for laparoscopic surgery as the slave manipulator and PHANTOM-Omni haptic device as the master robot. The second objective is to design a control algorithm for achieving high trajectory tracking which allows the surgeon to perform the operation with high accuracy.

This paper is organized as follows. In Section II, the description and kinematic solution of the slave robot are briefly presented. Positioning with Modified Rate Control technique as a teleoperation mapping technique is discussed in Section III. Hardware implementation, Software design and control algorithm which constitute the experimental setup are described in Section IV. In Section V, the real time results and

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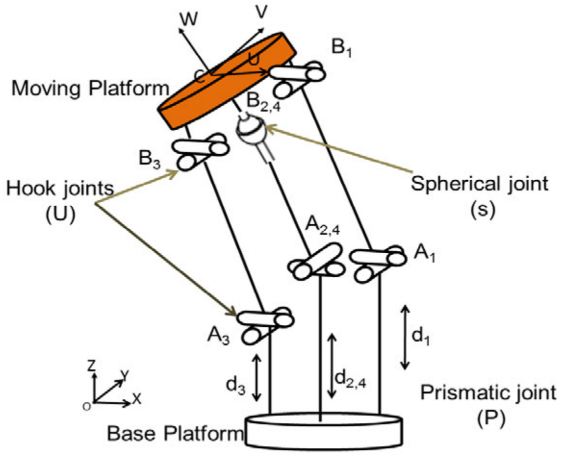

Fig. 1. Schematic diagram of the slave surgical robot (2-PUU_2-PUS)

the discussion of the motion and control of the 2-PUU_2-PUS surgical manipulator are presented. Finally, conclusions and future work are summarized in Section VI.

II. SLAVE SURGICAL ROBOT

The final implemented design of the surgical manipulator is 2-PUU_2-PUS architecture as shown in Fig. 1. The parallel manipulator consists of four legs; two legs are 2-PUU (each leg consists of one active prismatic joint and two consecutive passive hook joints respectively); the other two legs are 2-PUS (each leg consists of one active prismatic joint, one passive hook joint and one passive spherical joint respectively). Each leg is connected to the base platform with active prismatic (P) joint. Due to symmetry in the design, the bending angles in all directions are equal. The design of 4-DOF endoscopic surgical parallel manipulator, 2-PUU_ 2-PUS, is achieved using screw theory and Parallel virtual chain methodology in order to obtain larger bending angles and workspace size. For some considerations in fabrication process, the spherical joint is implemented in this small scale through one hook joint followed by one revolute joint whose axis is orthogonal to the two axes of the hook joint and intersect with them in one point. Fig. 2, illustrates the real model of the designed parallel surgical manipulator (2-PUU_2-PUS) in which its links are manufactured from annealed stainless steel.

For the purpose of controlling the parallel manipulator, a mathematical model of the inverse and forward kinematics is needed. Especially inverse kinematics has a vital and practical role in the control of the end-effector motion. The inverse kinematics problem deals with determining the required values of the actuated joints in order to reach a certain position and orientation of the end-effector. Supposing the values of position vector and the orientation matrix are known, one can solve for the required motion of the actuated joints d1, d2, d3, and d4. Fig. 3, shows the schematic of the slave robot chain. The transformation from the mobile platform frame to the fixed platform frame is expressed by a position vector P_c ,which is equal to OC, and a rotation matrix ${}^{b}R_m$:

Fig. 2. Real prototype of the surgical manipulator

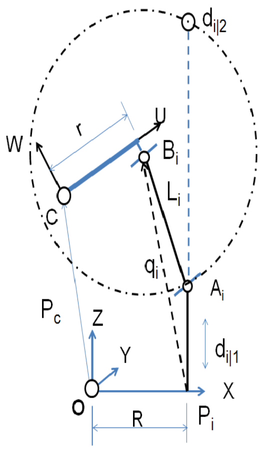

Fig. 3. Schematic of the slave robot chain

$$P_c = \begin{bmatrix} P_{cx} \\ P_{cy} \\ P_{cz} \end{bmatrix}, \qquad {}^{b}R_m = \begin{bmatrix} U_x & V_x & W_x \\ U_y & V_y & W_y \\ U_z & V_z & W_z \end{bmatrix}$$

The closed-form solution for the inverse kinematic of the 2-PUU-2-PUS parallel manipulator is found to be [8]:

$$d_i = q_i.Z - \sqrt{(q_i.Z)^2 - {q_i}^T.q_i + \ {L_i}^2} \tag{1}$$

where q_i is calculated as:

$$q_i = {}^{b}R_m.B_{im} + P_c - P_i \tag{2}$$

The forward kinematics of the proposed parallel manipulator is determined numerically based on the above closed form solution. Then, according to the inverse and forward kinematics analysis, the workspace of (2-PUU_2-PUS) parallel manipulator is obtained numerically.

III. TELEOPERATION MAPPING TECHNIQUE

Teleoperation system enables the operator to remotely control a slave robot interacting with the environment using another robot called the master robot as shown in Fig. 4. The

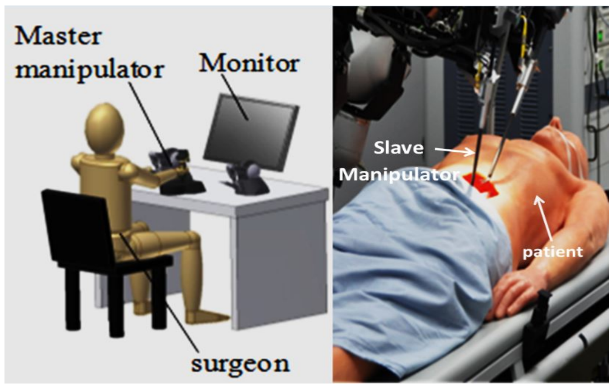

Fig. 4. Teleoperation system concept

two robots used in the teleoperation system may be identical or different in kinematics and workspace size as in [9],[10] respectively. The later one is the case when using PHANTOM-Omni haptic device as a master robot and a 2-PUU_2-PUS surgical manipulator as a slave robot. For the implemented system, the master haptic device workspace is larger than the workspace of the slave parallel manipulator. Also, teleoperation tasks are executed using the inverse kinematics of the slave parallel manipulator. Consequently, a convenient and efficient mapping technique is required to produce precise positioning and allow the surgeon to span the whole workspace of the slave parallel robot.

Various techniques have been proposed to solve the workspace mapping problem. Positioning with Modified Rate Control technique is one of these techniques that provides a simple and efficient method to solve the mapping problem based on dividing the workspace of the slave robot to overlapped sections. Inside each section the scaling factor can be designed to allow fine manipulation. However, moving from one section to another is performed using a switch in the PHANTOM-Omni haptic device. So, there are two modes of operation; fine motion mode where the switch is released and coarse motion mode where the switch is pressed and hold [11]. Positioning with Modified Rate Control technique is selected to be used as a mapping technique in our teleoperation system.

In Positioning with Modified Rate Control technique, the position of the slave robot end-effector is specified using the relation:

$$\vec{P_e} = K\vec{P_{ph}} + \vec{P_w} \tag{3}$$

where $\vec{P_e}$,$\vec{P_{ph}}$, and $\vec{P_w}$ are the position of the slave robot end-effector, the PHANTOM-Omni haptic device cursor position relative to the device frame, and the virtual workspace position relative to the world frame in mm respectively. K is a scaling factor that should be less than unity. For example, It is chosen to be set to 0.01 in our case to give high resolution and achieve fine manipulation.The value of this scaling factor K is adjustable. Its optimal value will be decided by the surgeon based on practical considerations.

The operation of the teleoperated system using this technique can be divided into two modes:

1) Fine Manipulation Mode: in which the switch in the PHANTOM-Omni haptic device is released. In this mode the virtual workspace position $\vec{P_w}$ remains constant and when the master haptic device is moved, the displacement is mapped to the slave robot. As the scaling factor is set to a small value as 0.01, the operator is able to perform fine manipulation inside a volume of the slave robot workspace equal to 0.01 of the master haptic device workspace. Typically this is a scaling control scheme.

2) Coarse Motion Mode : The operator should switch the operation to this mode when it is desired to operate in a volume in the slave robot workspace that can not be attained with the currently existing value of the virtual workspace position $\vec{P_w}$. To achieve this, the virtual workspace position $\vec{P_w}$ is updated when the switch in the master haptic device is pressed and held as described in the following:

- Just after the operator press the switch, the position of the master haptic device is recorded as $\vec{P_i}$. This position is the starting point of the leading vector.
- After any small movement of the master haptic device, the final position is recorded as $\vec{P_f}$. This position is the ending point of the leading vector.
- A unit vector in the direction of the leading vector can be computed by knowing the starting and ending points of the leading vector, this is done according to:

$$\vec{u} = \frac{\vec{P_f} - \vec{P_i}}{\left\| \left(\vec{P_f} - \vec{P_i}\right) \right\|} \tag{4}$$

  where $\vec{u}$ represents a unit vector in the direction of the leading vector.

Then, the virtual workspace position $\vec{P_w}$ is updated using the following equation:

$$\vec{P_w} = \vec{P_w} + s.\vec{u} \tag{5}$$

where s is a constant that indicates the speed by which the virtual workspace position $\vec{P_w}$ is moving. If the operator recognizes that he reaches the desired location, he can release the switch and resume working in fine manipulation mode. Also, the value of the constant speed s is adjustable to be appropriate for the surgeon. i.e. its optimal value will be decided based on practical considerations. In this way the coarse motion mode can be considered as a rate control scheme with constant speed.

This technique is implemented in this way for two reasons. Firstly, in coarse motion mode, constant speed does not require a displacement of the haptic device except at the beginning, i.e. a very small displacement is required in order to specify the direction of motion. Thus, the two modes are working independently from each other. Secondly, after the end of coarse motion mode and switch to fine manipulation mode the end-effector mostly will be at the same position of the haptic device but with the new virtual workspace position $\vec{P_w}$ which means that there is no offset relative to the new $\vec{P_w}$.

IV. EXPERIMENTAL SETUP

In order to investigate the feasibility of the teleoperation system that uses the manufactured 4-DOF parallel manipulator (2-PUU_2-PUS) as a slave robot, a practical experiment has been accomplished using Positioning with Modified Rate Control technique and PID controller. An experimental setup is established as illustrated in Fig. 5. The details of the hardware, software, and control algorithm used are explained in the following subsections.

A. Hardware implementation

In building the experimental setup, the following equipments are used:

1) PHANTOM-Omni haptic device (SensAble Technologies Inc.): It is used as a master controller for the end-effector tool attached to the manipulator. It is a haptic device with a 6-DOFs positional sensing. Its workspace is larger than 160 W x 120 H x 70 D mm. Its hardware interface allows real time operation using C++ programming language and 3D Touch OPENHAPTICS® TOOLKIT.

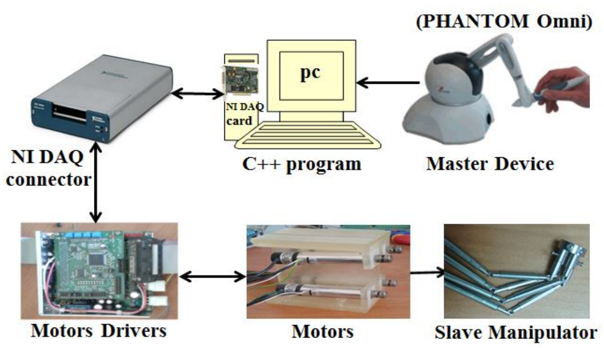

Fig. 5. Experimental system building blocks

2) 2-PUU_ 2-PUS parallel manipulator: This is the manufactured surgical manipulator to be used as the slave device.

3) PC: The controller console is programmed to make a mapping between the workspaces of the master and slave robots, solve inverse Kinematics of the slave 2PUU_ 2PUS parallel robot, and control the motion of the slave robot according to the motion of the master device.

4) NI PCIe-6323 X Series Data Acquisition : It is used to interface between the slave manipulator and PC, receive data from the sensors and send commands to the actuated motors of the manipulator depending on the control algorithm.

5) Connector Block - Screw Terminal SCB-68A : Since NI Data Acquisition card (DAQ) does not have direct signal connectivity, a connector block is needed to act as an interface between system signals and DAQ device also provides easy access to the inputs and outputs of the DAQ card.

6) AC Servomotors EA-1771A-C100: It has a high resolution small incremental encoder that can achieve ultra-high positioning. Four motors are used to actuate the four prismatic joints of the surgical manipulator.

7) Chiba Precision's open collector type driver, EAD-08C-012 for the AC servomotor: This product has been developed as a dedicated driver for the AC servomotor used. Four units of this drivers are used; one for each motor.

8) Input Power Supply unit : It is used to supply the motor drivers with DC24V & DC5V.

B. Software designed program

Software is needed to interface with the hardware and to collect, analyze, present and store the measurements. C++ programming language under Windows7 operating system is used to establish communication between the manipulator and the PC. At the beginning a sample program was developed for commanding the four actuators of the prismatic joints and monitoring the current position in real time. Step, Sine, Trapezoidal signals are used as a desired values to mimic the motion of the surgeon. Finally the library of the haptic device (hdu.lib) is linked to the program in order to communicate with the PHANTOM-Omni haptic device and follow the motion of the surgeon.

C++ program is developed for commanding the four prismatic joints according to the flow chart shown in Fig. 6. PID

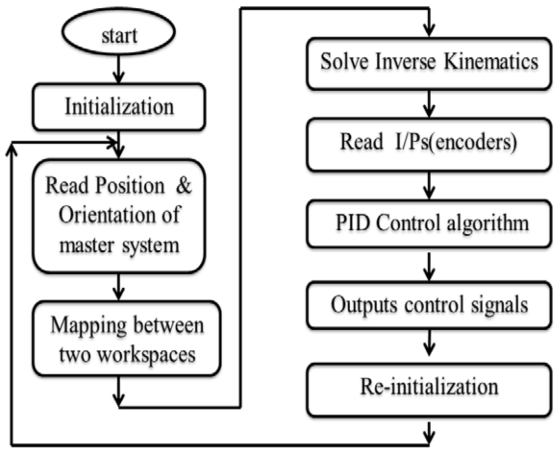

Fig. 6. Control system flowchart

Controller is used to control system position. It calculates the error $e(t)$ as the difference between the commanded value and the measured value. The controller aims to minimize the error value by adjusting the control signal $u(t)$ that controls the prismatic joints. The control signal $u(t)$ is calculated according to the following equation:

$$u\left(t\right) = k_p.e\left(t\right) + k_d.\frac{de(t)}{dt} + k_i.\int e(t)dt \tag{6}$$

where k_p, k_i, k_d are Proportional gain, Integral gain, and derivative gain respectively. Four PID controllers are used; one for each prismatic joint. Tuning the parameters of the PID controller is implemented using Ziegler-Nichols method. Then, fine tuning is required to adjust the final response.

According to the flowchart, the program starts with initializing all needed parameters. Then, the program reads the position and orientation of the master device and send it, through the workspace mapping technique, to control the motion of the motors. This in turn locate the end-effector of the surgical manipulator at the required position and orientation. This process Continues as long as the system is running.

V. EXPERIMENTAL RESULTS

For easy and comfortable operation, the operator can select the current position as the zero position. So, by using a push button, the operator can determine the starting point and the program takes this point as the origin point for the operation. Before pressing the home button, any movement in the master device will not mapped to the slave side. An experiment with the surgical manipulator system has been performed according to the following scenario.

The operator presses the home position button after 5.7 sec, so there is no movement of the actuators before that time. After pressing the home position button, the movement of the master device is mapped to the slave side using fine manipulation mode. After 35.5 sec, the operator recognizes that he needs to move to another volume in the workspace so he presses the switch in the haptic device and makes a small movement toward the target location. As a result, the slave manipulator moved in this direction by a constant speed. This is typically the coarse motion mode. After approximately 44.5 sec, the operator realizes that he reaches the desired area so he releases the switch and comes back to the fine manipulation mode.

Fig. 7, illustrates the experimental response of the four actuators as a result of moving the master device according to the previous scenario. The desired values are obtained from the inverse kinematics solution and the actual values are measured using the incremental encoder of each active prismatic joint. This figure illustrates the feasibility of the new 4-DOF parallel manipulator (2-PUU_2-PUS) also proves that the control algorithm can achieve high trajectory tracking. Fig. 8, presents the error of tracking between the desired and actual values of the actuators positions.

Fig. 9, shows the resultant motion of both PHANTOM-Omni haptic device and (2-PUU_2-PUS) parallel manipulator as slave robot. It should be noticed that firstly any random movement of PHANTOM-Omni haptic device is mapped to the volume 1 of slave robot workspace. Then, the operator presses the switch in the haptic device and make a small movement, such that the slave robot moves toward volume 2. When the slave robot reached to volume 2, the operator releases the switch and again the slave robot follows the haptic device.

Fig. 10, demonstrates the changes in the x, y, and z components of each point in the trajectory of the slave robot, with the corresponding component of the master device in the period of moving from volume 1 to volume 2. It can be noticed that, after the operator presses the switch in the PHANTOM-Omni at the moment of 35.5 sec, the slave robot moves with a constant speed while the master device remains fixed. Also, if the operator moves the master unintentionally, this motion will not be transferred to the slave side. Finally, when the user releases the switch the slave robot will follow the master device as before. It should be noted that the operation is continuous and the transition from fine manipulation mode or coarse motion mode to the other mode is smoothly performed. Also, During the experimentation, the bending angles have reached more than $\pm 90^o$ equally in all directions due to the symmetry in the mechanical design.

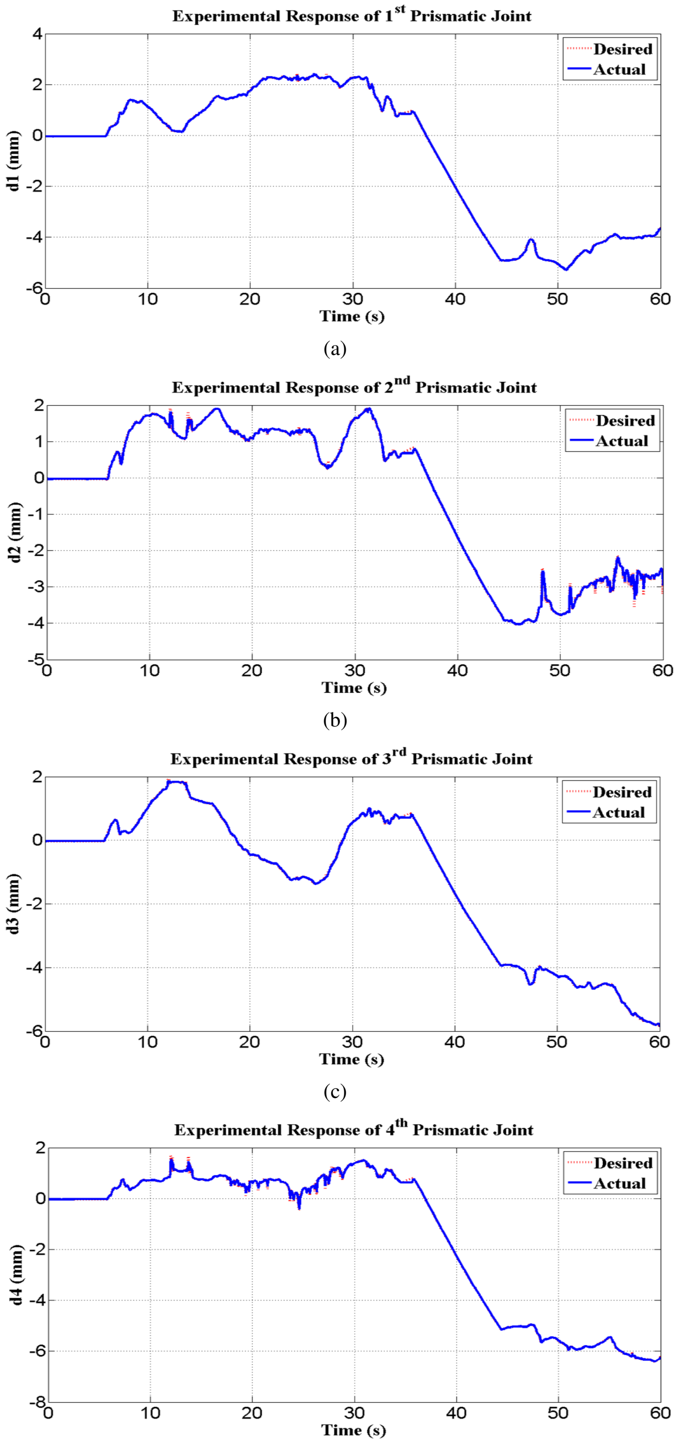

Fig. 7. Experimental Response of the actuators: a) d1 response, b) d2 response, c) d3 response, and d) d4 response.

VI. CONCLUSION

The complete experimental setup of a teleoperated surgical system has been built using 2-PUU _ 2-PUS 4-DOF parallel manipulator as the slave robot and PHANTOM-Omni haptic device as the master robot. The practical implementation uses Positioning with Modied Rate Control technique as a mapping technique between the master and slave workspaces. In this initial state, PID controller is used to control the motion of the slave robot. The experimental results obtained confirmed the feasibility of the design of surgical manipulator that has bending angles more than $\pm 90^o$ in all directions, So the workspace of the mechanism is larger than that of the current state of the art endoscopic manipulators. Finally, the results ensure the efficiency of the mapping technique and the designed controller in spanning the slave workspace with accurate positioning, smoothness and high tracking. As a future work, a gripper with force sensor will be attached to the surgical manipulator. The addition of position and force feedback will facilitate the operation of the system. Also a hybrid intelligent control system will be used to improve the performance and make it robust against uncertainties.

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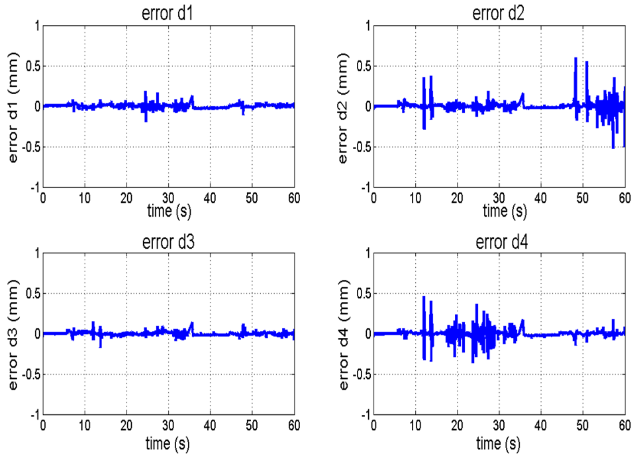

Fig. 8. error between the desired and actual values of the actuators

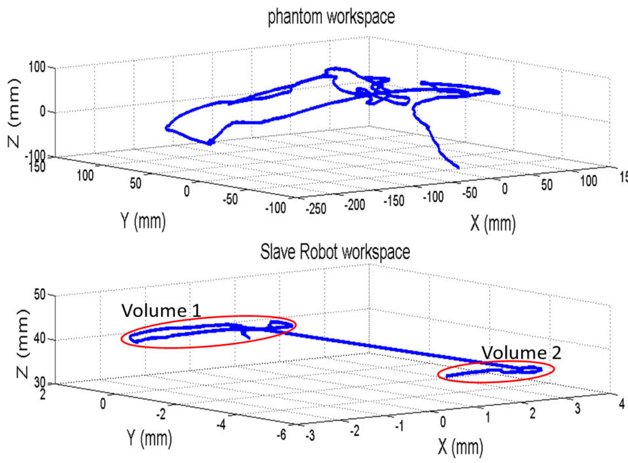

Fig. 9. Motions of the phantom device and the slave robot

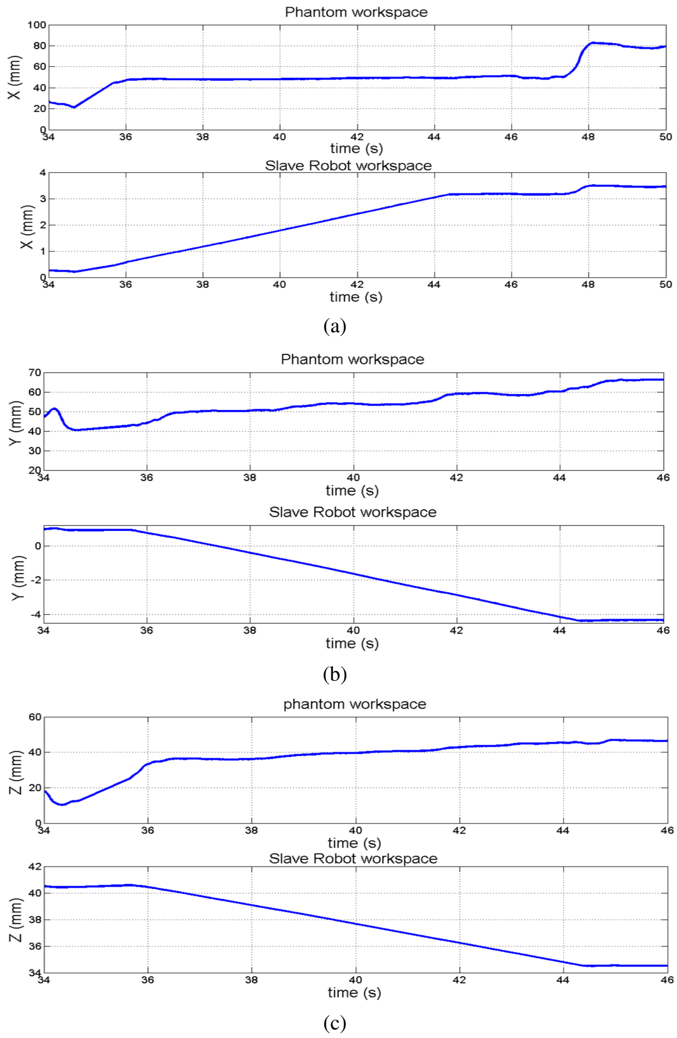

Fig. 10. Trajectories of phantom position and 2-PUU_2-PUS end effector position: a) X component, b) Y component, and c) Z component.

to Egypt-Japan University of Science and Technology (E-JUST) for guidance and support.

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