Design, Implementation and Testing of Master Slave Robotic Surgical System

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ABSTRACT

The autonomous manipulation of the medical robotics is needed to draw up a complete surgical plan in development. The autonomy of the robot comes from the fact that once the plan is drawn up off-line, only the servoloops control the actions of the robot online, based on instantaneous control signals and measurements provided by the vision or force sensors. Using only these autonomous techniques in medical and surgical robotics remain relatively limited for two main reasons: Predicting complexity of the gestures, and human Safety. Therefore, Modern research in haptic force feedback in medical robotics is aimed to develop medical robots capable of performing remotely, what a surgeon does by himself. These medical robots are supposed to work exactly in the manner that a surgeon does in daily routine. In this paper the master slave tele-robotic system is designed and implemented with accuracy and stability by using 6DOF (Six Degree of Freedom) haptic force feedback devices. The master slave control strategy, haptic devices integration, application software designing using Visual C^{++} and experimental setup are considered. Finally, results are presented in terms of the stability, accuracy and repeatability of the system.

Key Words: **Tele-Robotic Surgery, Kinematics Analysis, Haptic Force Feedback Devices.**

1. INTRODUCTION

Master/slave technique based surgical system is also known as remote surgery or tele-robotic surgical system [1]. Tele-robotic system is used to control robotic manipulator from remote location for performing such serious surgeries due to unavailability of surgeon [2]. These types of systems are controlled from remote location by the surgeon and surgeon is able to perform specified surgical task such as needle insertion, cutting, drilling etc. [3]. This kind of surgical task needs accuracy, stability and reputability [4]. Slave surgical robot follows the movement of the master manipulator which is controlled by surgeon hands drive during surgical task. Traditional neurosurgical rigid stereo tactile frame was used to manual needle insertion into the brain [5]. This system is replaced by automated needle intervention robotic system driving by the robotic system according to predefined position by neuromata (Renishaw Ltd , UK)

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and the ROSA (MedTech, France) [6]. Above systems have much limitation because of patient position and orientation on operating table. For removing these limitations a system has to be introduced which is controllable by the surgeon during surgery [7]. Another important factor is haptic force feedback during remote surgeries, and for this purpose haptic devices play an essential role [8].

The proposed prototype master/slave surgical system has capability to perform surgical procedure such as needle insertion, cutting and drilling accurately and precisely. In this paper, we discuss the designing and implementation of basic master-slave prototype surgical system consisting of a human operator master side, slave manipulator at surgical side, controlling and recording the activity of the system by software designing, and surgical procedure environment. In such system the information exchange between operator and the remote environment is made possible with transparency. In visual C^{++} the controller is design for monitoring and recording data of master and slave position motion in text file and Matlab is used to draw graphs. Simultaneously master slave controller is also designed to control the slave manipulator with stability and repeatability.

2. MASTER SLAVE SURGICAL SYSTEM DESIGNING PROCEDURES

The basic master slave system is presented in Fig 1. The information exchange is controlled by the controller in the form of master and slave position, velocity, and force as shown in Fig. 1.

In Fig. 1 *fm* is the force provided by the human on haptic device, *pm/Vm* is the input position and velocity information of the master device for the controller. *ps/Vs* is the slave manipulator input control signal and finally *fs* is the slave manipulator force which is applied on the surgical procedure environment.

The master/slave surgical system has many issues during any surgical procedure such as position tracking, velocity and force estimation between human and surgical environment [9]. By providing position tracking control techniques, the system is able to deliver transparency between human and the remote surgical environment [10].

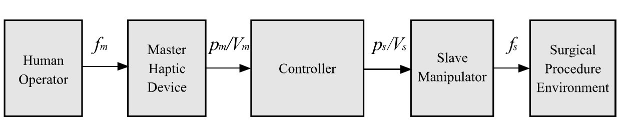

FIG. 1. BASIC MASTER/SLAVE SYSTEM

The proposed master/slave system is based on accurate position information of the master for transmitting to the controller. The slave is driven by the commands which are given to the controller and controller must be able to read position of the slave. Master and slave must have position sensing with full gravity compensation and ovoid interference from parasitic torques generation. Dedicated sensors are needed to provide accurate position after drift-free calibration.

Master and slave manipulator are shown in Fig. 2 with control application. The master and slave system are based on 6DOF, three are active based on position and three for orientation which are passive. In this project 3DOF Active portion is used.

3. MASTER SLAVE CONTROLLER DESIGNING

In order to control slave end-effector to track the master HD (Haptic Device), the PC (Proportional Controller) is designed. The proposed tele-robotic control system is presented in Fig. 3. The F_{surg} (Force Inputs) is applied by the surgeon/operator to the master HD. The Master HD changes its position and the position sensors inside the HD calculate the original position of the hand according to applied force from the operator. PM_{in} (Master Positions) are the input of the controller, which then (Ks) multiplied with PM_{in} for scaling of the input (default value of Ks is 1.00) of the HD. The PMK_{in} is the input of difference. The difference is calculated between the reference point (PMK_{in}) and the slave actuator position PS_{out} (measured by the slave position sensors). The difference is multiplied by the proportional coefficient of the controller (Kp). Slave SA_{in} (Actuator Input) is simply the difference of master and slave positions

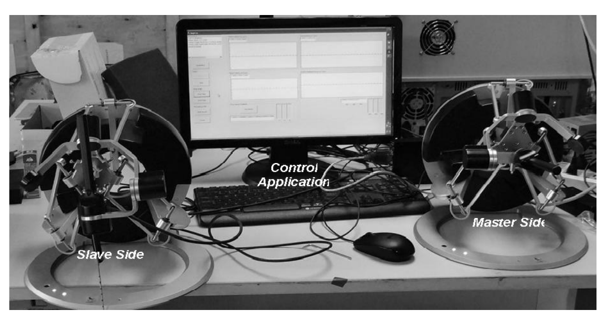

FIG. 2. PROPOSED MASTER/SLAVE SYSTEM

with proportional coefficient of controller (Kp). This difference is multiplied with Kp to obtain the new position of slave actuator PS_{out}. There is no advancement of the manipulator, whenever the difference is zero. The block controller diagram is shown in Fig. 3.

This difference is generated, whenever slave actuator is not able to reach desired position or more than normal torque required due to environmental constraint. The position difference communication latency between the master and slave is very low up to 1.5 KHz. The master and slave systems are connected with usb 2.0 port upto 2kHz update rate.

4. APPLICATION SOFTWARE DEVELOPMENT FOR MASTER SLAVE SYSTEM

After designing the control strategy, the most difficult task to implement in real world. Visual C^{++} 2008 is used to design application software for master and salve control system. Visual C^{++} provides GUI (Graphical User Interface) environment for developing application. MFC (Microsoft Foundation Class) from *Microsoft Corporation* and Robotic and Haptic SDK (Software Development Kit) from *Force and Dimension Corporation* are employed to design and implement the application software. Application software is based on GUI environment and equipped with monitoring recording and graphical facility. The software enhanced the transparency and visual feedback of the slave side. The operator or surgeon became more confident and comfortable during surgical procedure. Application software for master slave control is shown in Fig. 4.

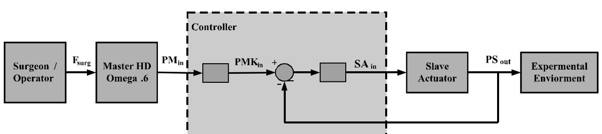

FIG. 3. MASTER SLAVE CONTROLLER

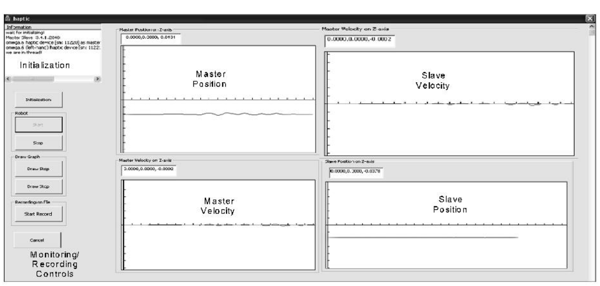

FIG. 4. APPLICATION SOFTWARE FOR MATER/SLAVE CONTROL

The Fig. 4 shows that the designed software application is able to control, monitor and recording the position and velocity of the master and slave. Application software is able to monitor the three dimension information of the master and slave and draw the graph according to selected axis. The procedure of the program designing can be summarized as follows:

(1) Define specified path to SDK files such as drdc.h, drdc.h and required .dll files in the visual C^{++} properties. Then the controllers are defined according to button as shown in Fig 5.

(2) Initialization of the Master and Slave Devices as shown in Fig. 6.

{
Get SDK version for devices
For loop {two devices initialization
Open device;
Get system type;
Device Initialized;
Device Start;
Define Role (Master=1 or Slave=0);
}}

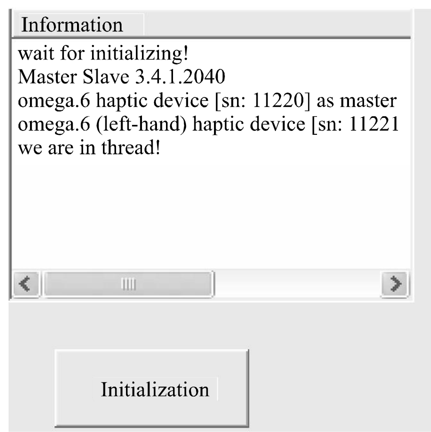

FIG. 5. ROBOT INITIALIZATION INFORMATION

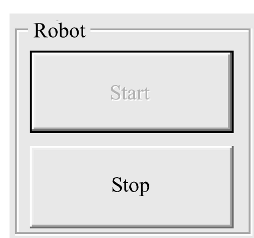

FIG. 6. ROBOT START PROGRAM BUTTON

(3) Start Master and Slave Robot by using Thread-1

```
{
While loop {for position and velocity update
Get linear velocity from master;
Get Position from master;
Track the Position and velocity to Slave from Master with Scaling Factor (default is 1.00);
Get position and velocity from Slave;
}}
```

(4) Exit thread by stop button. There are four main steps of master slave control program as mentioned above and the other parameters such as scaling and stiffness can be changed according to procedure requirement. The other control buttons are used for graphical plotting over the visual studio front screen and recording the measurement and testing.

5. EXPERIMENTAL MEASUREMENTS AND TESTING ENVIRONMENT

To ensure the stability, flexibility, repeatability and delay of the slave side with respect to master handheld device, the experimental setup is established. The master and slave system is checked under the observation of data collection from master slave devices.

The position, velocity, error, standard deviation and mean values are recorded and plotted for system stability. The following experimental setup was designed to collect data as shown in Fig. 7.

The experiments are based on individual axis movement of the master and slave in free air for calculating the position and velocity error between the master and slave manipulator. Haptic device axis movements are shown in Fig. 8.

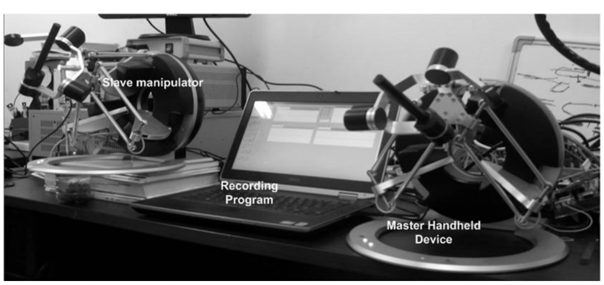

FIG. 7. EXPERIMENTAL SETUP IN FREE AIR

The data is recorded up to four decimal places for analyzing the accuracy, repeatability and stability of the system. Following graphs show the slave tracking and its error with respect to master HD. The result shows the system is stable, reliable and repeatable during experiment in free air. The position values are shifted to positive side for calculating error.

5.1 X-Axis Measurement

Master and Slave position tracking on x-axis (Inward<<>>Outward) along error, standard deviation and mean with respect to Master Manipulator is shown in Fig. 9.

The Fig. 9 shows the smooth movement of slave manipulator, the maximum error is about ±0.0038, the standard deviation and mean almost negligible.

Master and Slave velocity tracking on x-axis along error, standard deviation and mean with respect to Master Manipulator is shown in Fig. 10. The velocity is controlled by hand therefore, it is random. In velocity graph, when line crosses over the x-axis at zero level then its means the direction of the HD devices is changed from positive region to negative region or vice versa.

The Fig. 10 shows the smooth velocity tracking of slave manipulator, the maximum error is about ±0.0040, the standard deviation and mean almost negligible.

5.2 Y-Axis Measurement

Master and Slave position tracking on y-axis (Left<<>>Right) along error, standard deviation and mean with respect to Master Manipulator is shown in Fig. 11.

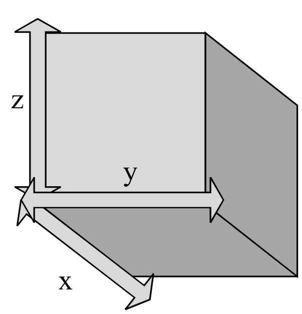

FIG. 8. AXES MOVEMENT

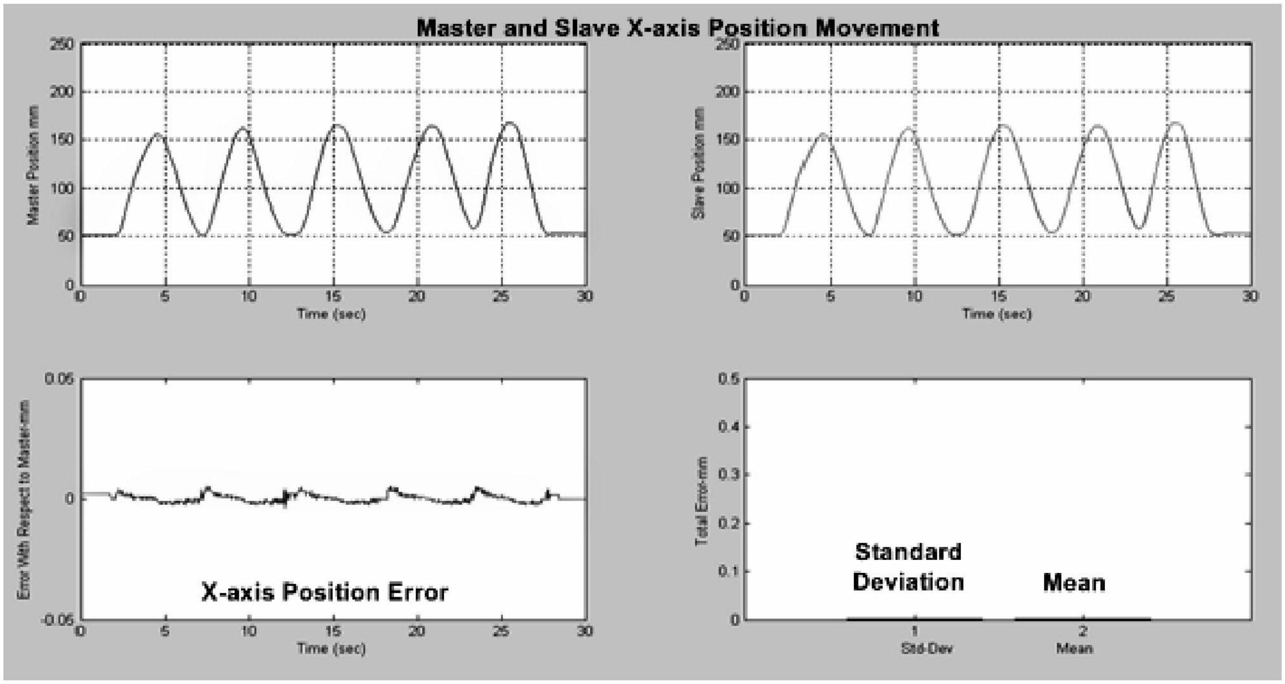

FIG. 9. MASTER SLAVE POSITION TRACKING ON X-AXIS

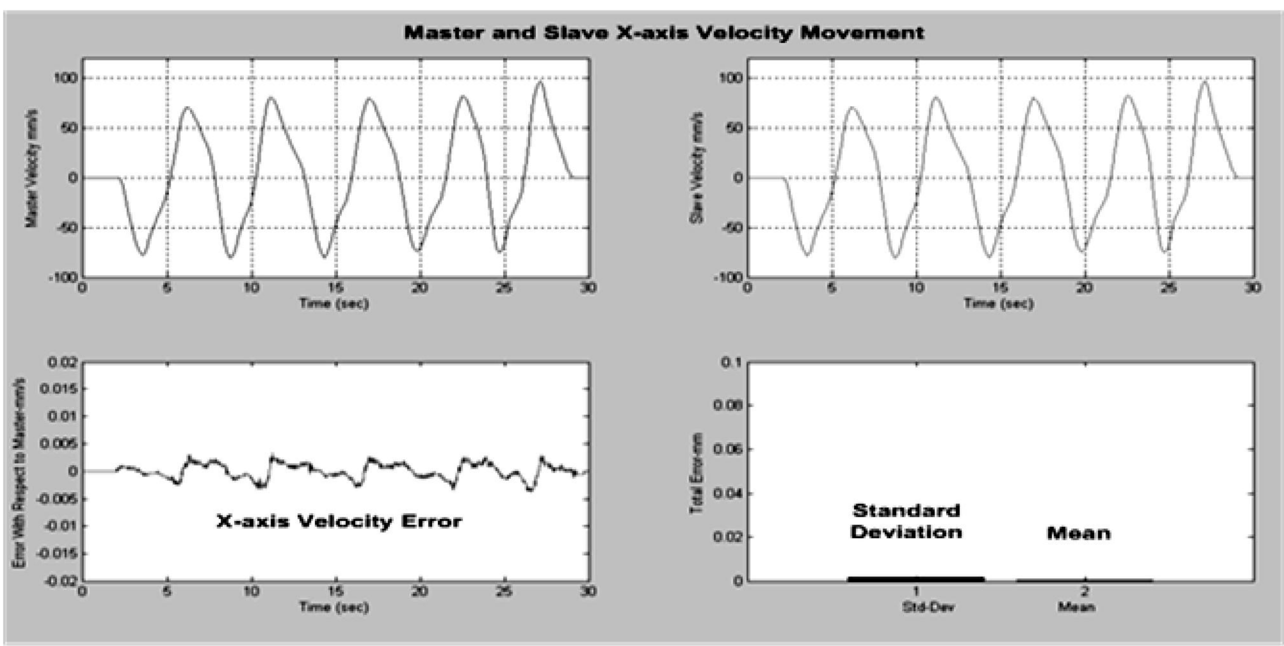

FIG. 10. MASTER SLAVE VELOCITY TRACKING ON X-AXIS

Fig. 10 shows the smooth movement of slave manipulator, the maximum error is about ±0.0250, the standard deviation and mean is low.

Master and Slave velocity tracking on y-axis beside error, standard deviation and mean with respect to Master Manipulator is shown in Fig. 11. The velocity is controlled by hand therefore it is random. In velocity graph, when line crosses over the x-axis at zero level then its mean the direction of the HD devices is changed from +ve region to –ve region or vice versa.

The Fig. 12 shows the smooth velocity tracking of slave manipulator, the maximum error is about

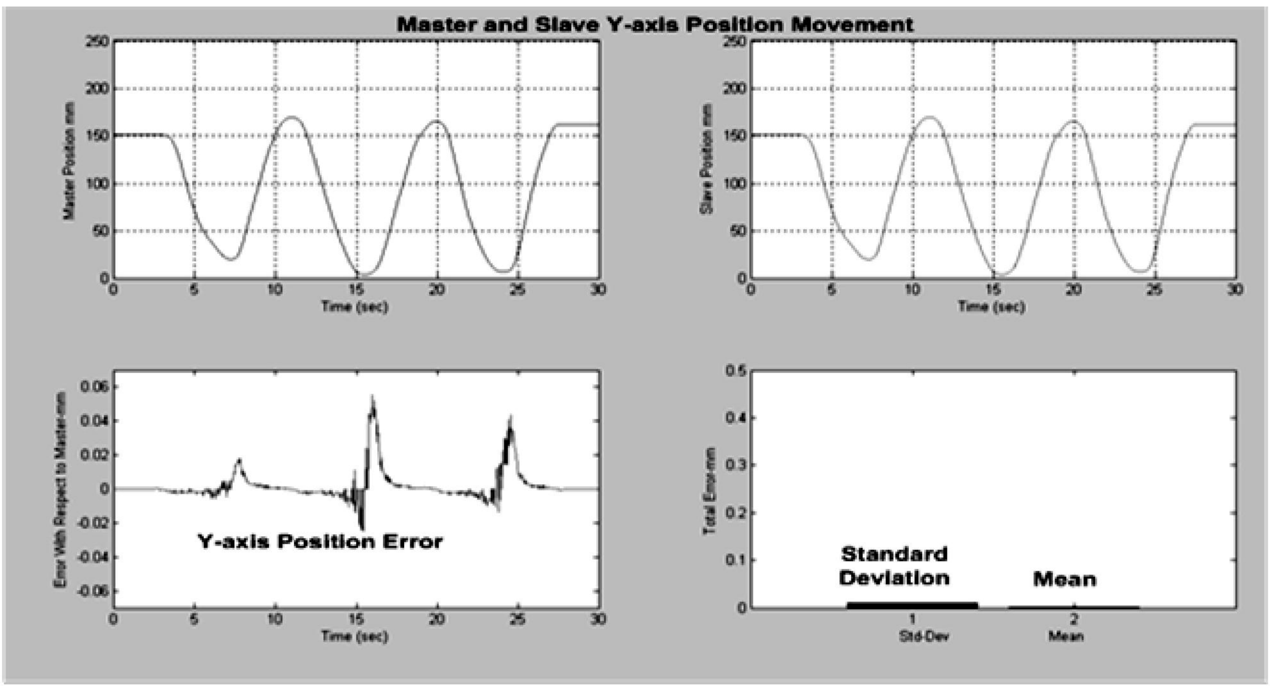

FIG. 11. MASTER SLAVE POSITION TRACKING Y-AXIS

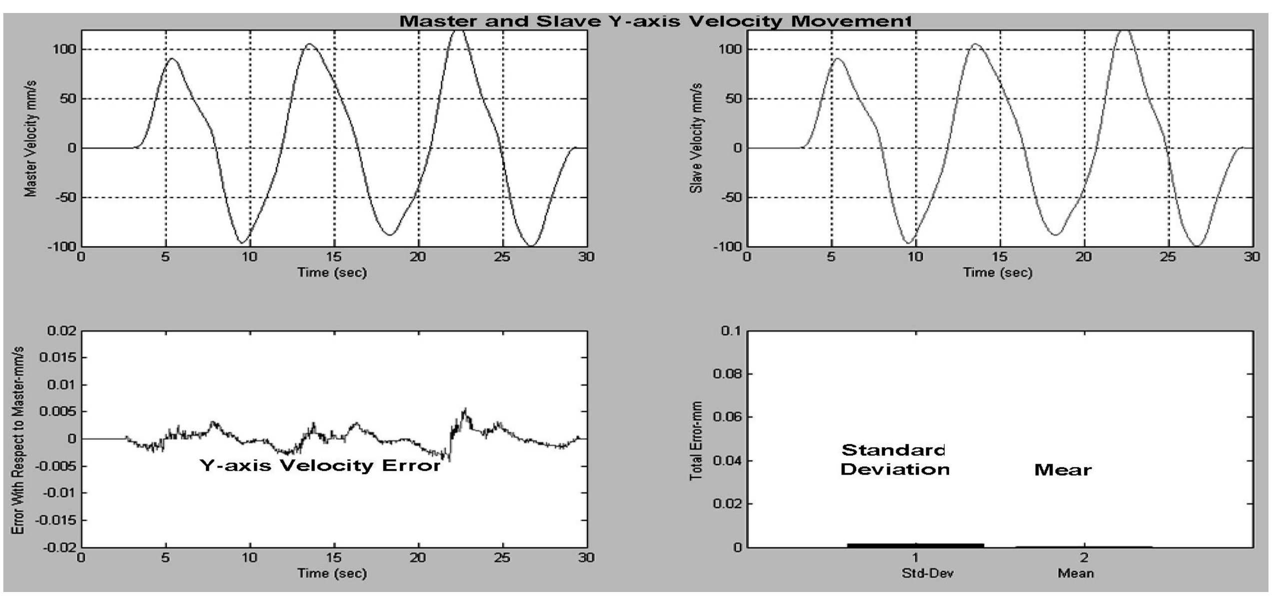

FIG. 12. MASTER SLAVE VELOCITY TRACKING Y-AXIS

±0.0040, the standard deviation and mean almost negligible.

5.3 Z-Axis Measurement

Master and Slave position tracking on z-axis (upward<<>>downward) along error, standard deviation and mean with respect to Master Manipulator is shown in Fig. 13.

Master and Slave velocity tracking on y-axis beside error, standard deviation and mean with respect to Master Manipulator is shown in Fig. 14. The velocity is controlled by hand therefore, it is random. In velocity graph, when line crosses over the x-axis at zero level then its mean the direction of the HD devices is changed from +ve region to –ve region or vice versa

The Fig. 14 shows the smooth velocity tracking of slave manipulator, the maximum error is about ±0.0048, the standard deviation and mean almost negligible.

5.4 3D-Measurements

The proposed system is also able to provide movement in 3D environment. The following measurements are performed in free air for calculating the system error in the free 3D environments. Three dimension movements of the medical robot are very helpful for performing cutting drilling, milling of the bone and minimum invasive surgical task. Therefore, the presented master slave surgical system is able to perform operation in three dimensions rather than one dimension at a time.

The position measurements of the system in three dimensions are shown in Fig. 15. The maximum error with respect to master is about 0.0020 mm and the mean and standard deviation of the error almost negligible.

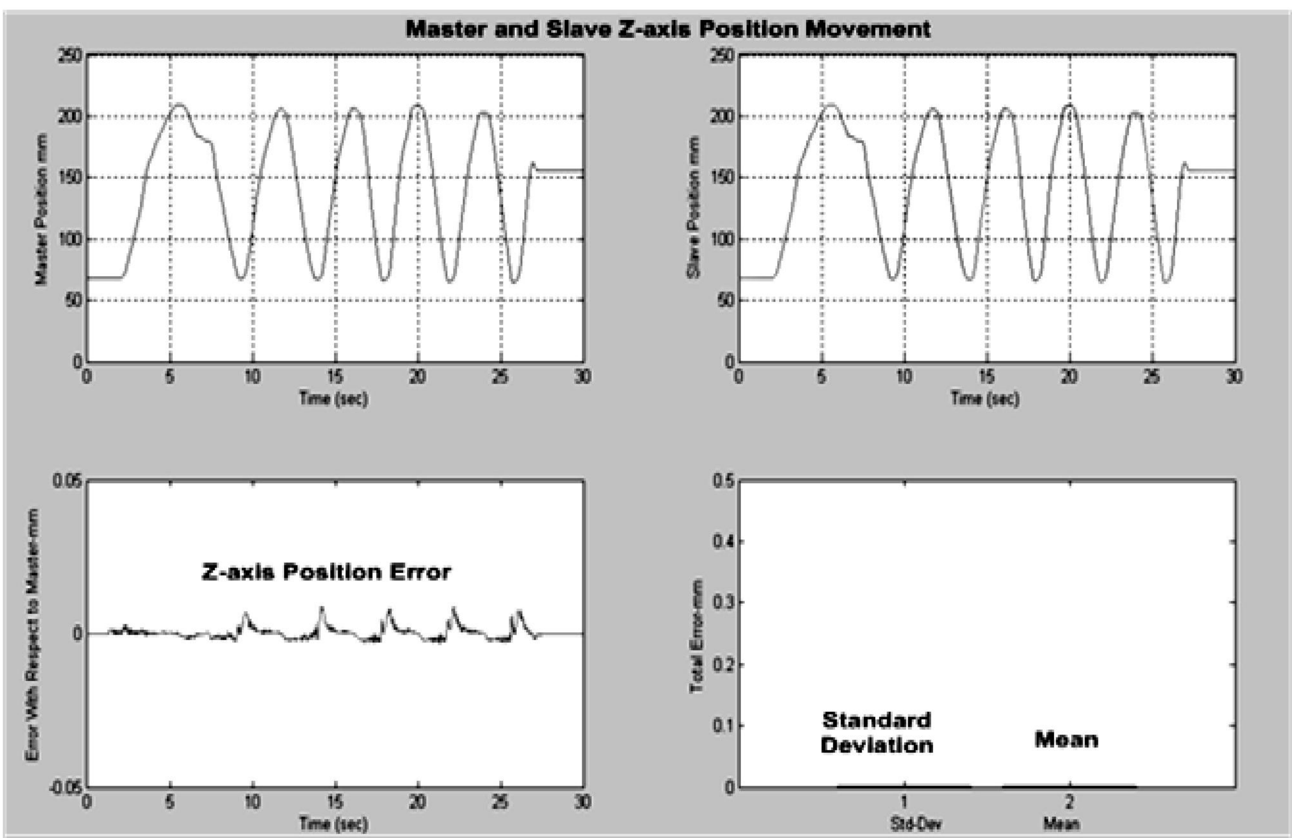

FIG. 13. MASTER SLAVE POSITION TRACKING Z-AXIS

The Fig. 13 shows the smooth movement of slave manipulator, the maximum error is about ±0.0029, the standard deviation and mean is low.

The velocity measurements of the system in three dimensions are also shown in Fig. 16. The maximum error with respect to master is about 0.0024 mm/s and the mean and standard deviation of the error almost negligible.

The above calculation of the proposed system shows the satisfactory result with respect to each individual axis and as well as three dimension. The maximum error is 0.025 mm at y-axis.

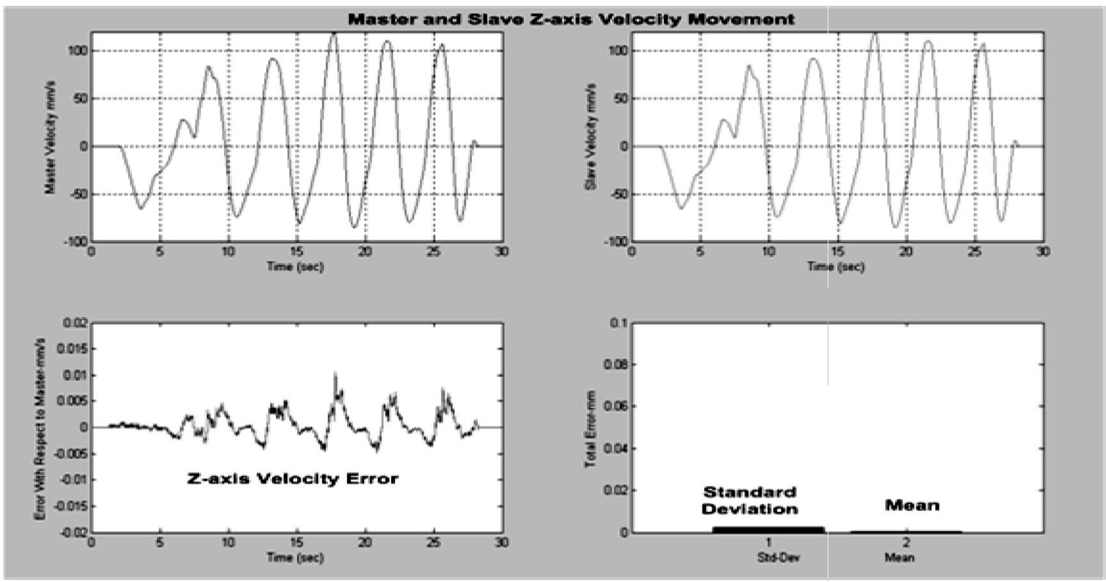

FIG. 14. MASTER SLAVE VELOCITY TRACKING Z-AXIS

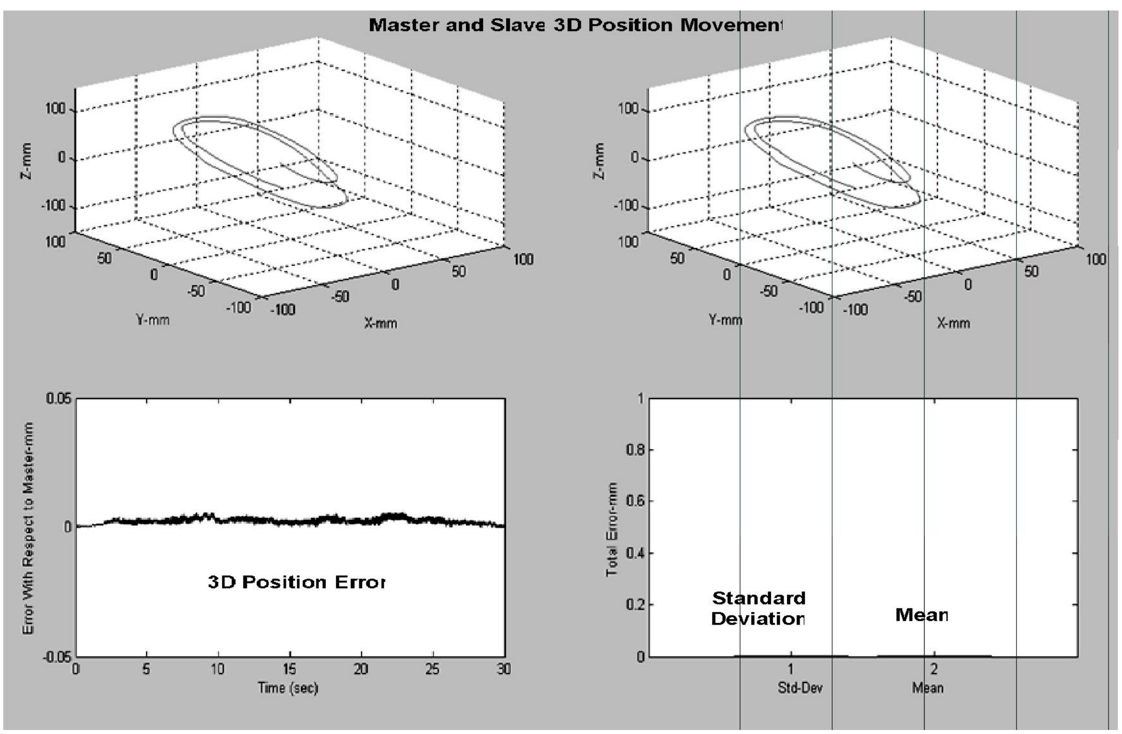

FIG. 15. 3D MASTER SLAVE RANDOM POSITION ERROR, SD AND MEAN

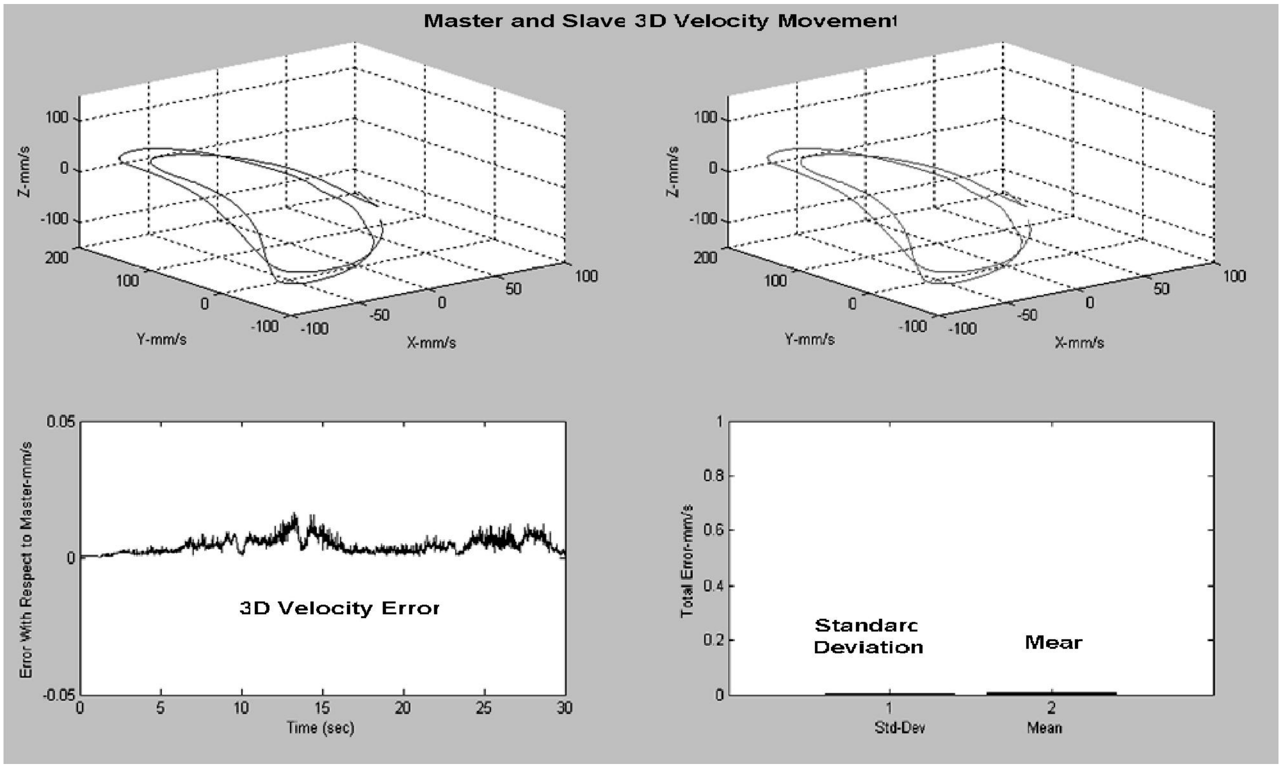

FIG. 16. 3D MASTER SLAVE RANDOM VELOCITY ERROR, SD AND MEAN

6. CONCLUSION

This paper present a master slave system designing and implementation by considering haptic devices. Designing controller and software implementation with GUI interface are mentioned and discussed. The experimental result of the system in free air with respect to position and velocity error are also shown. Results show the stability, repeatability and transparency of the proposed system in the experimental environment. The designed and implemented surgical system will be used for needle insertion surgery with force feedback effect.

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