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Design and Implementation of Probe Driver Teleoperative Force Feedback System

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Abstract

The basic need of neurosurgery is to insert the probe into the key hole linearly for performing functional neurosurgery, trigeminal neuralgia surgery, biopsies, deep brain stimulation, and stereo-EEG. Recently, tele-robotic systems have been introduced to assist surgeon during invasive procedures to obtain desired results. In this paper, a linear probe driving tele-operative system with force feedback is proposed. The proposed system is highly accurate, stable, and safe and provides haptic transparency to the surgeon during its operation. The master slave architecture, control system and software application are designed to inject and eject probe driving trials. The experiments are performed on a piecewise linear Plasticine model. The accuracy, stability, repeatability of the system and haptic force feedback fidelity are discussed in the results.

Keywords: *Trigeminal neuralgia surgery, Haptic, Tele-Robotic Surgery, force feedback fidelity*

1. Introduction

In surgical procedures, small probe or electrodes are driven into the key hole of the skull. (i.e. functional neurosurgery, trigeminal neuralgia surgery, biopsies, deep brain stimulation, and stereo-EEG). Tele-robotic system provides assistance to perform such surgical task. Traditional neurosurgical procedure was based on manual insertion of the needle by using rigid stereotactile frame [1]. The above system was replaced with autonomously needle driving robotic system according to predefined position by neuromata (Renishaw Ltd, UK) and the ROSA (MedTech, France) [2]. NeuroDrive and Alpha-Drive (Alpha-Omega, Nazareth, Israel) devices are designed to automatically insert the EEG (Electroencephalongraphy) electrode into the brain for signal recording purpose with inserting depth of about 40mm. However, this depth is not enough for neurosurgical intervention (require advancement of the needle up to 110mm in the brain) [3]. Master and Slave telerobotic system had been intended and Slave follows the surgeon action using master handheld device but no haptic interaction is introduced [4]. Tele-operated system with tactile force feedback are planned, surgeon get tactile force feedback when interacts with patient organ [5]. Master side haptic transparency depends on the mechanical characteristic and dynamics of the haptic device [6]. Due to dissimilar master and slave mechanical structure, the linearity between them in terms of position and velocity of the manipulator is not possible [7]. Haptic transparency also depends on the quantified impedance and admittance of the master and slave environments [8]. However, transparency of the slave side is based on the force sensing during needle insertion and transfer the actual intensity with particular direction towards the master side.

In telerobotic surgery, the tactile force feedback is based upon two techniques, first, to place force sensor at slave actuator and the second, is to calculate the position errors between the master and slave manipulator. In general, the force sensor is installed on actuator or at the tip of the shaft for tactile sensing [9]. In Low Energy Neurofeedback System (LANS), the load cells are placed on the actuator shaft. The force sensor is not suitable to be placed on the tip of the shaft due to many constraints such as size, shape, biocompatibility and sterilization [10].

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Force sensors are placed on a gripper in laparoscopic surgery for achieving the sense of gripping [11, 12], however, given solution is not appropriate for key hole neurosurgery. Force feedback can also obtained by calculating the difference between errors in the positions of master and slave. Besides, position errors are not so easily computed owing to environmental resistance and system dynamics [13, 14]. In [15], the position error force feedback system is presented but the accuracy and stability are not mentioned. The actual dynamics model of the slave actuator and master should be known to get position error accurately [16, 17].

In this framework, the prototype system is designed using two haptic devices by assigning the role of master and slave. Some modification is performed on slave actuator for establishing the rigid contact with biopsy probe and force sensor. Position error is calculated and its amplitude is transferred to the surgeon's end as tactile feedback for estimating the experiments. The control system is designed for transparency and stable communication between master and slave devices; therefore, surgeon is able to control the position of the actuator transparently and accurately. Meanwhile, he is also capable to feel the tactile force sensing during standard surgical biopsy needle insertion and ejection. The system is tested on a brain like mimicking tissue using Plasticine at constant temperature. Finally, the results are shown about the accurate movement of the needle according to surgeon handheld haptic device positions and transparency of the tactile force feedback system.

2. Material and Method

The objective of the present telerobotic system is to drive standard biopsy needle into one dimension key hole without the loss of kinesthetic perception. Needle is driven by the input of surgeon handheld haptic device.

2.1. Mechanical Hardware

Before starting to design the telerobotic bilateral surgery, it is important to consider that the accurate position information of the master manipulator must be available and transmitted to the slave manipulator without any delay. The slave manipulator is driven according to the given position to the master. The position and force sensor data from the slave manipulator are needed to established the transparent and stable haptic force feedback element for master manipulator. Keeping these issues in mind, the novel tele-robotic needle intervention system for neurosurgery are designed and implemented.

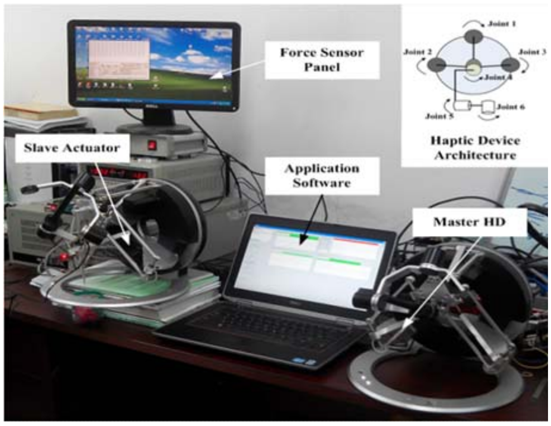

Figure 1. Experimental Hardware

In this project, there are two haptic devices. One haptic device works as master manipulator while the other one as a slave actuator. Due to similar mechanical and dynamical structure of the system, we achieved linear response from the control algorithms. Omega.6 haptic devices, designed by Force Dimension, are used in this project [18]. These devices are six degree of freedom (6-DOF) haptic device, of which three are active and three are passive.

Joint 1, 2 and 3 of the devices are used on both sides for controlling the slave actuator. The experimental arrangement and device architecture are shown in Figure 1. The purposed system is able to move in three dimensions; however, to perform needle intervention experiments, it only needs one direction. Therefore, the system is restricted to single plane movement in z-axis. The system provides 180mm workspace on z-axis. The objective of the present tele-robotic system is to drive standard biopsy needle into one dimension key hole without the loss of kinesthetic perception. Needle is driven by the input of surgeon handheld haptic device.

The important blocks of the system are given below:

1. Operator: controls the position and velocity of the master haptic device (HD).
2. Master HD: input the position and velocity and receive force feedback from the controller.
3. Controller: responsible for slave motion and force feedback magnitude and dimension.
4. Slave Actuator: follows the position and velocity from master HD.
5. Mechanical Adapter: designed for further instrument attachments.
6. Force Sensor: One dimension Bengbu Force Sensor (JLBS) is used to measure the contact response of the needle at interaction with sample.
7. Shaft & Needle: Surgical biopsy needle (Bard Magnum Tissue Biopsy Needle) attached with shaft.
8. Sample: Plasticine

For performing experiments, some physical alterations have been made on slave actuator. Triangular adapter are designed and attached with haptic device. Mechanical shaft, force sensor and biopsy needle are also adjusted with adapter. The system components are shown from master manipulator to slave needle in Figure 2 and 4.

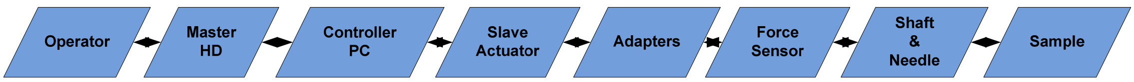

Figure 2. Block Diagram of the System

2.2. Control System

In order to control slave end-effector to track the master HD, the proportional controller (PC) are designed. The proposed tele-robotic control system is presented in Figure 3. The position inputs (P_{surg}) are given by the surgeon/operator to the master HD. The motor encoders of the master HD, after inverse kinematics conversion, transfers position values of the hand to the controller. Master positions (PM_{in}) are the input of the controller, which then scaling factor (K_s) multiplied with PM_{in} for scaling of the input (default value of K_s is 1.00). The error between the reference point PMK_{in} and the slave actuator position PS_{out} (measured by the slave encoders) is multiplied by the proportional coefficient of the controller (K_p). Slave actuator input (SA_{in}) is simply the difference of master and slave actuator positions (PMK_{in} - PS_{out}). This difference is multiplied with proportional coefficient (K_p) to obtain the new position of slave actuator PS_{out}. There is no advancement of the needle, whenever the error is zero.

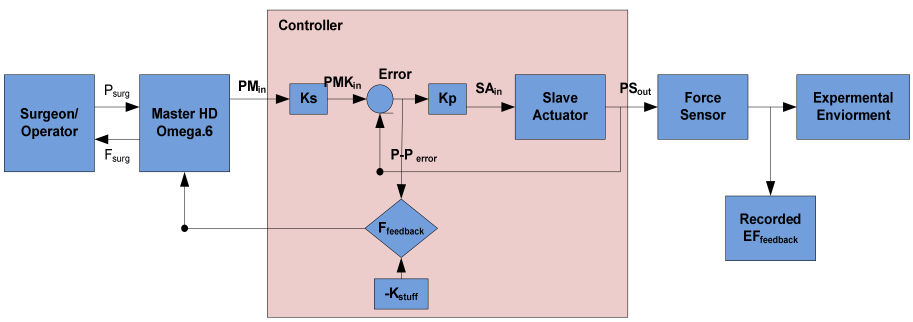

Figure 3. Block Diagram of the Control System

There are two ways to calculate and apply the Force feedback on master side, Position error (P-P error) and Environmental Force sensor feedback ($EF_{feedback}$). Position error is based on the difference of the master and slave encoder's data. This error is generated, whenever slave actuator is not able to reach desired position or more than normal torque required due to environmental constraint. The position error communication latency between the master and slave is very low up to 1.5KHz and both devices are connected with usb 2.0 port. The second feedback is based on force sensor attached with the before the needle adapter. Force sensor is connected with serial port and the communication latency is high, therefore, force data is recorded not transmitted for force feedback. The K-stiffness depends on the type of physical models used in the experiment. K is higher for hard object and lower for soft object. K-stiffness is the multiplier with force feedback factor and related with haptic device for better tactile feeling.

3. Experimental Procedure
3.1. Setup

Experimental tests are performed by using Bard Magnum (2.1mm diameter) brain biopsy needle. Initially advancement of the needle is tested in air for checking the stability of the position movement and force feedback data due to system assembly constraints. A Plasticine sample is prepared for performing experiments. Another calibrated force sensor (Flexi Force sensor manufactured by Tekscan) is installed under the load cell for calculating as the reference force signal. The biopsy needle intervenes into single-axis, the z-axis, according to master HD. The physical alterations with slave actuator and experimental setup are shown in Figure 4.

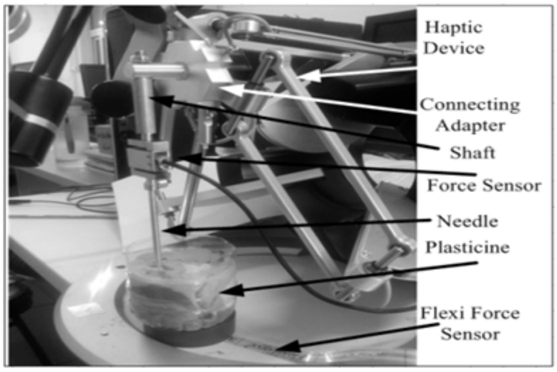

Figure 4. Experimental Setup on Slave Actuator

3.2. Application Software

Computer application is designed for controlling, monitoring and recording the master/slave movements, velocities, and force estimation. Application software is able to present real time numerical and graphical information about positions, velocities and force feedback of the needle intervention. The communication refresh rate between the computer and the master device is 2.0KHz. Refresh rate computation is based on function calls that apply a force on the haptic device. The average refresh rate of the slave actuator control loop is about 1.5KHz. Surgeon can watch and control almost all parameter during experiment as shown in Figure 5. During designing of the application software keep in mind that it should be easy to control and understand for user. Initialization of the master and slave manipulators, monitoring and recording controls, master and salve current position numerically and graphically, force feedback intensity bar and graph, finally velocity of master manipulator are presented in following application software as shown Figure 5.The recording algorithm frequency for master slave positioning, master velocity and position error is about 10Hz which is set by timer

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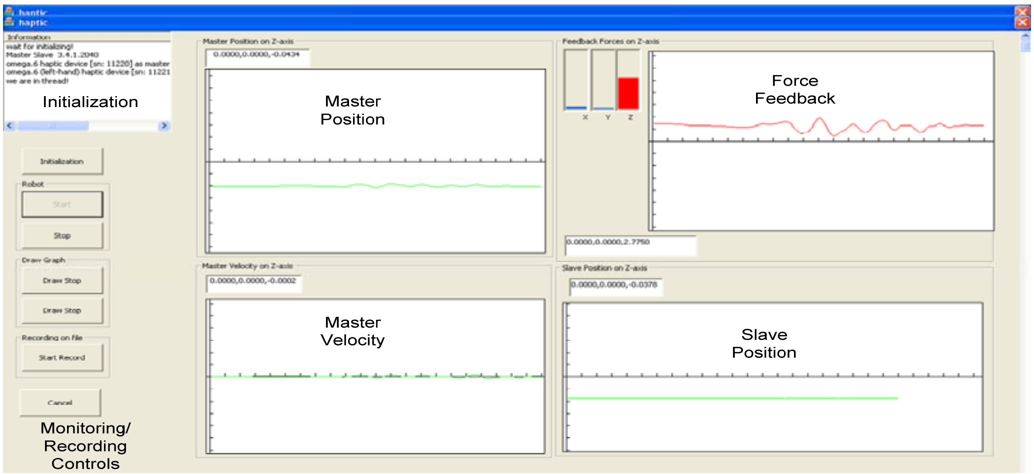

Figure 5. Application Software

4. Result and Discussion

Two types of experiments are performed. First, tests are based on to check the system's response in air. The experiment was repeated five times and average values are shown in the plots. Master HD, Slave actuator position, position error, force sensor and master HD velocity graphs are presented. Graphs shown in Figure 6 are for movement between two fixed points.

In these results, the experimental validation of tele-operated slave actuator probe in air is shown. The master HD position and slave actuator position coordination graphs show the accuracy and linear movement with respect to time. Micrometer fluctuations are shown in position error graph that is acceptable for surgery. The force sensor graph shows small fluctuations less than 0.010N and variable velocity based on operator movement.

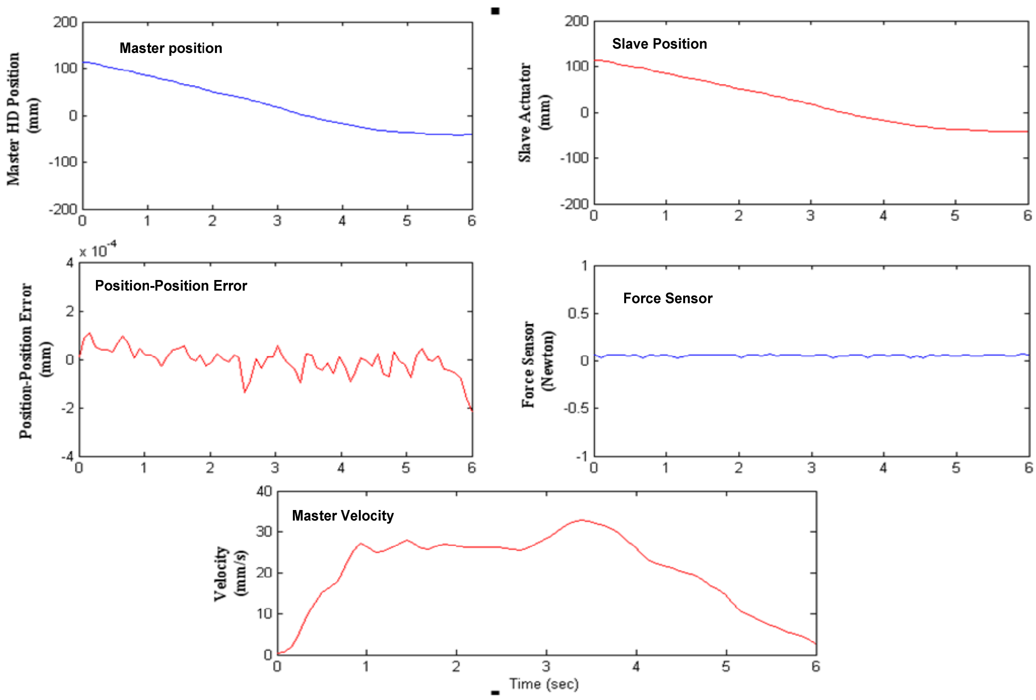

Figure 6. System Response in Air

The second experiment is based on needle insertion into the Plasticine sample. In this experiment, the needle is injected and ejected five times. Following graphs show the response of the system.

The needle is injected about 40mm inside the sample. During needle penetration, variation in position error and force sensor is seen. Maximum force during needle insertion is about 1.9014N and ejection is 0.0N. Velocity changes in all trials and depends on user handling of the device. Z-axis vs Position graph shows the maximum force feedback area between 70 to 85 mm in this area the max force felt on the device due to needle insertion into the material.

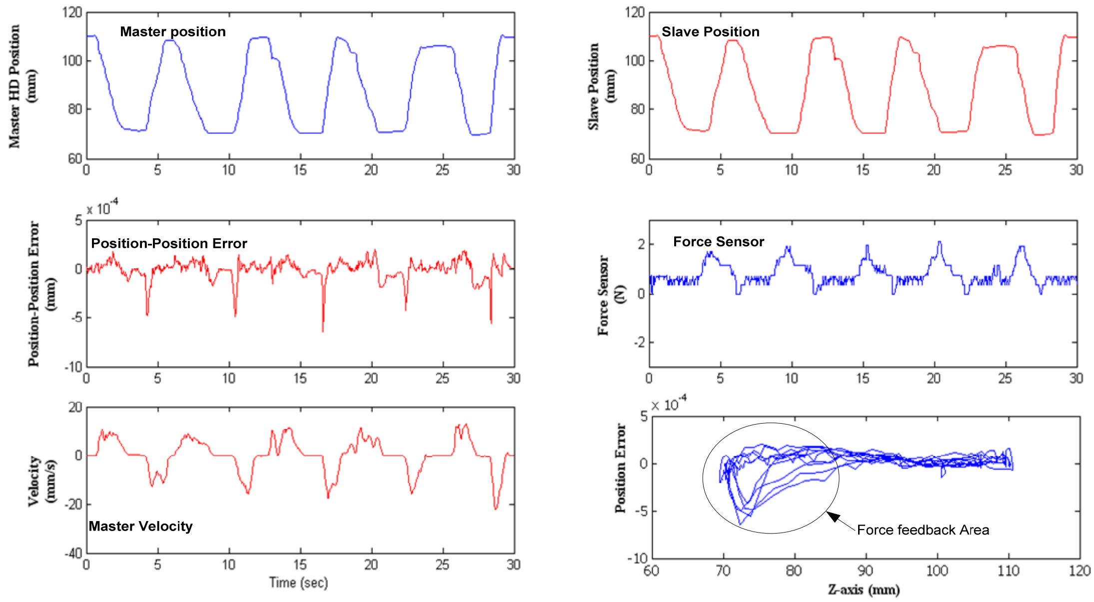

Figure 7. System Response in Plasticine

5. Conclusion

This paper presents design and implementation of needle driven tele-robotic surgical system with force feedback. Operator feels more transparency and stability in term of slave actuator response and force feedback due to position-position error. Operator controls the velocity of the system according to requirement. Master force feedback haptic loop and slave control loop frequencies are increased to achieve swift and smooth system response. The maximum force is 1.9014N applied on the sample and maximum difference is $-7x10^{-4}$. The maximum force feedback feel at 70 to 85mm in the sample as mention at Figure 6. The force and position error are also depend on the applied velocity from the operator at master HD. In future, further improvement in the resolution of the force sensor and increase the response time to realize proper communication with haptic device.

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