Sindh Univ. Res. Jour. (Sci. Ser.) vol. 47 (3) 425- 430 (2015)

SINDH UNIVERSITY RESEARCH JOURNAL (SCIENCE SERIES)

Six Degree of Freedom (6-DOF) Force Sensor Based Haptic Force Feedback Robotic System

S. A. ALI, A. M. SOOMRO[++]*, A. N. KHIZER**, Z. ABYDIN***,B. BALOCH****

Department of Biomedical, Mehran University of Engineering and Technology, Jamshoro, Sindh, Pakistan

Received 14th January 2015 and Revised 26th June 2015

Abstract: Self-directed and programmed robotic system is not compatible to perform any simple or complex surgical procedures. The autonomous system is mostly based on sudden control signals which are mostly based on vision, force sensors, navigation systems etc. Therefore, it has many borders in surgical procedures. However, modern research in robotic surgery has introduced on-line/real time haptic force feedback technology, which can perform complex surgical procedures with real time haptic force feedback sense. These medical robots are supposed to work exactly in the manner a surgeon does in daily routine. This paper is based on the master slave tele-robotic system, designed and implemented with 6-DOF force sensor. Force feedback strategy is designed and applied with accuracy and stability for surgical results. In this paper, control strategy, haptic devices and force sensor integration, application software designing by Visual C++ and experimental setup are discussed. Finally implemented system is verified on different animal tissues and material to validate the system stability, accuracy and repeatability.

Keywords: Tele-robotic surgery, 6-DOF Force Sensor, Haptic force feedback

1. INTRODUCTION

Master and Slave surgical system and Position-Position Difference based haptic force feedback system were designed and the results were checked in last two papers (Syed, *et al.*, 2014) (Syed, *et al.*, 2013). The results have stability, reliability and repeatability along with force feedback element in terms of position and force feedback factor. In this paper we are going to introduce the force sensor based force feedback system (Masamune, *et al.*, 2001). The new architecture is introduced in this chapter for producing haptic force feedback element based on 6-DOF force sensor at master handheld device (Rossi, *et al.*, 2005). Force sensor is placed on the slave manipulator behind the surgical tool (biopsy needle). Force Sensor control strategy is applied to establish haptic force feedback at end-effector of the slave manipulator. In this paper, the small changing in slave mechanics to place the sensor in the manipulator for performing different procedures such as needle injecting and ejection into the different types of experimental structures, are discussed. The controller will be designed to produce transparent haptic force feedback using force sensor and the software development according to propose strategy (Dombre, *et al.*, 2003).

The proposed prototype master/slave surgical system has capability to perform surgical procedure such as needle insertion, cutting and drilling accurately and precisely(Mahvash, *et al.*, 2007). . In this paper, we will 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 force feedback activity of the system by software designing, and surgical procedure environment (King, *et al.*, 2009).

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 and force element 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. FORCE SENSOR BASED FORCE FEEDBACK SYSTEM

The Force Sensor (FS) based master slave system is presented in (**Fig.1).** The Force information is sent to controller to achieve transparent haptic force feedback on master handheld haptic device during slave interaction with environmental constraint .The M3813A six axis force/torque sensor is used to develop haptic force feedback system. The block diagram and the implementation of the force sensor in the slave side of the suggested FS haptic system are shown in fig.1. F*m* is the force applied by the human on haptic device; pm/Vm is the position and velocity information of the master device. This information is used as an input of

[++]Corresponding Author's email: amjad.ali@faculty.muet.edu.pk
*Department of Electrical Engineering, Mehran University of Engineering and Technology, Jamshoro, Sindh, Pakistan
**Department of Electronics Engineering, Mehran University of Engineering and Technology, Jamshoro, Sindh, Pakistan
***Department of Mechanical Engineering, Mehran University of Engineering and Technology, Jamshoro, Sindh, Pakistan
****Department of Statistics, Sindh Agriculture, University, Tando Jam

the designed controller in first step. The controller produces equivalent voltage signal to the 3-DOF slave actuator (Cps) with respect to input position, then slave starts moving to desired position. The refresh rate of the master slave system is about 1.5 KHz to 2 KHz.

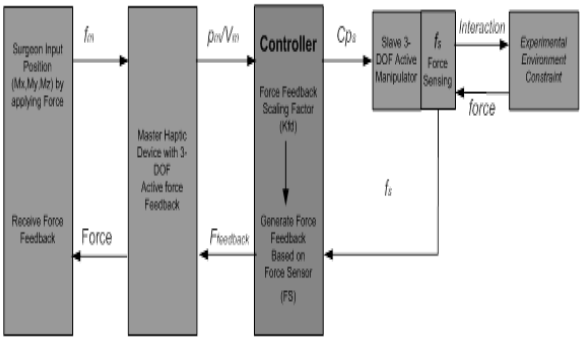


Fig.1. Force Sensor based Haptic Force Feedback System

The force sensor is placed with end-effector of the slave side behind the biopsy needle as shown in (**Fig .2).**

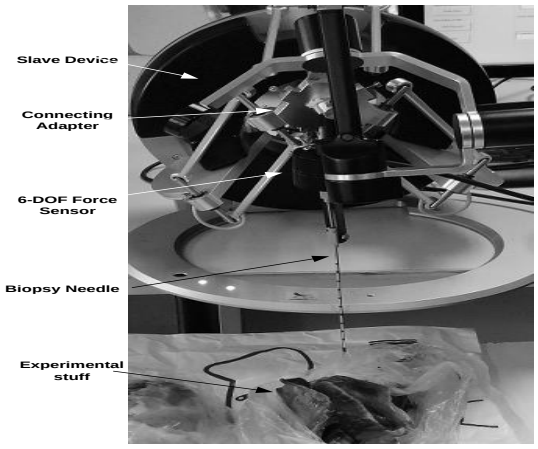


Fig.2. Force Sensor based Haptic Force Feedback System

Whenever biopsy needle interacts with environmental constraint such as injection or ejecting into the piecewise model, the contact force signals are produced. This contact force transfers to the force sensor and the force sensor converts into some voltage levels and the voltage levels are transmitted to the controller for further processing. Controller transforms this information into force feedback scale according to haptic device and force feedback effects can be sensed on handheld master haptic device.

3. FORCE SENSOR BASED FORCE FEEDBACK CONTROLLER SLAVE

The Force Sensor based controller depends on the real force from the force sensor. The refresh rate of the controller should be high as much as possible in terms of slave force sensor. In proposed force sensor based surgical system, the force sensor is placed between slave end-effector and surgical tool. When surgical tool (surgical needle or blade) interacts with the sample, the force is transferred to the sensor and the sensor generate some voltage level proportional to the applied force from the surgical environment. These voltage levels are transmitted to the controller and controller transforms or converts this voltage level to meaningful information for the master haptic device. The master haptic device responds according the force applied to the sensor . The force sensing based controller diagram is shown in (**Fig. 3).**

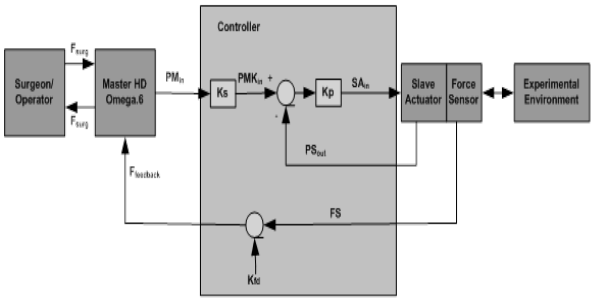


Fig. 3. Force Sensor based Haptic Force Feedback Control System

As mentioned earlier, the proportional controller (PC) is designed to control slave end-effector to track the master haptic device (HD). The proposed tele-robotic control system with force sensor based haptic force feedback system is presented in Fig 3. The force inputs (F_{surg}) are given by the surgeon/operator to the master omage.6 HD. The Master HD changes its position and the position sensors inside the HD update the original position of the hand according to applied force from the operator. Master positions (PM_{in}) are the inputs of the controller. Scaling factor (K_s) is used to increase or decrease workspace of the slave side (default value of Ks is 1.00), therefore Ks is multiplied with PM_{in} 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 (K_p). Slave actuator input (SA_{in}) is simply the difference of master and slave positions with proportional coefficient of controller (K_p). This difference is multiplied with K_p to obtain the new position of slave actuator PS_{out}. The refreshing frequency of the system is high to get real time movement without time delay. On the other hand, the force sensor is placed with the slave side to make force feedback whenever environmental constraint occurs. The refreshing rate of the force sensor must be same as master haptic loop. Finally stiffness coefficient (K_{fd}) factor is included to increase or decrease the stiffness according the surgical procedure on the haptic device.

Application Software Development for Force Sensor based Haptic Force Feedback System

After designing the control strategy to force sensor based force feedback system, the most problematic task in this technique is to employ force sensor in the real world. There are two applications which have to be integrated for information exchange. The force sensor application is also designed in Visual C++ 2008 language for maintaining the uniformity and improve data exchange rate between master slave and force sensor application. Visual C++ 2008 is used in software designing. Visual C++ provides Graphical user interface (GUI) environment for developing application. *Sunrise Auto Safety Technology Co. LTD* (SRI) provides application programming Interface (API) to program, calibrate, and interface with computer. The force sensor supports CAN Bus or RS232 communication with different baud rate. The default Baud rate of RS232 is 11522bps and this rate can be changed by using UARTCFG command. In addition, Microsoft Foundation Class (MFC) from *Microsoft Corporation* and Robotic and Haptic Software development Kit (SDK) from *Force and Dimension Corporation* are used to design and implement the application software. Application software should be equipped with monitoring and graphical facility; hence the user can visualize the motion and feels the force feedback effect on the screen and hand respectively. Software enhances the transparency and visual and haptic force feedback from the slave side. The operator or surgeon becomes more confident and comfortable during surgical procedure.

As shown in **(Fig.4)**, the application software is mostly same as in master slave control software. The additional feature is force sensing based force feedback presentation on the developed software and haptic force feedback on master HD in real time. The Force sensing data acquisition software is also designed and integrated with the main software for real time force data exchange. The procedure of the additional program designing is summarized as follows.



Fig. 4 . Application software for force sensor based force feedback system

1) In the main haptic force feedback program the "RUN SENSOR" control button is available. By clicking this button, a new force sensor program is opened as shown in fig.4. The name of this application is M8125-Demo.
2) There are different types of control available such as button, editor, combo boxes and etc.
3) "Open Port" control button is used to start the communication with RS232 port. Before pressing, set the Port Name and Baud rate by using combo-box.
4) If no error message on the "Rich Edit Window" then Config System button is pressed. Config system button is programmed to calibrate and decouple the sensor according to required condition.
5) Finally "Start Real Time" control button is pressed to get continued force data from the sensor.
6) In same thread: we calculate the force feedback amplitude by following formula.

$$FFB = -\mathrm{K}fd(\mathrm{FS})/\mathrm{K}s \qquad (5.1)$$

Here, *FS* is force sensor, K*fd* is stiffness coefficient of the haptic device, and *Ks* is the scaling factor.
7) At right side of the application, CH1 CH2 and CH3 are used to get and show the x, y, and z axis force data respectively. However, CH4, CH3, and CH6 are shown in the torque data.
8) The first three components are used to established force feedback on mater haptic device, therefore these data element are transferred to the main program.

Experimental Measurements and Testing Environment

In this section we performed test and measurement to validate the force feedback using force sensor.

3.1 Force Sensor Calibration:

Before starting the experiment, the force sensor has to be calibrated according to standard process. We applied different standardized weight (forces) with the reference of hundred gram (100gm) approximately equal to one newton (1N) and so on. In **Fig. 5** shows the standardized weight and Newton VS time graph. The weigh is applied over the z-axis of the sensor as shown in green line, blue and red lines belong to X and Y axes respectively.

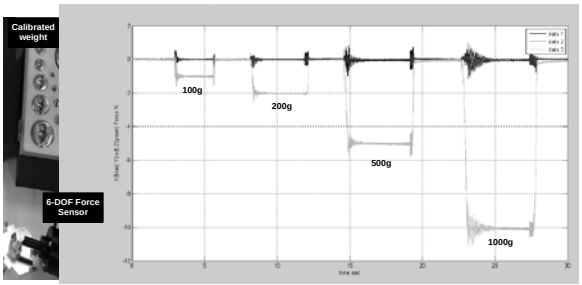


Fig.5 : Calibrated weight and Newton vs Time Graph

3.2 Experimental Results in Free Movement

Before starting the experiment on different structure, the first experiment is conducted in free air to calculate the offset error of the force sensor in the manipulator. The experimental results are shown in (Fig.6). The first graph is about master random positioning in millimeter (mm) with all axes. The maximum error from the force sensor in free space movement is about less than ±0.20N on each axis as shown **(Fig .6).** These errors occur due to random jerks during change of the direction of the master device.

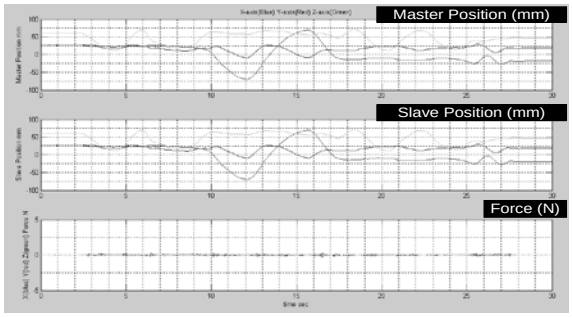


Fig. 6. FS Experimental Results in Free Movement

5.3 Experimental result on pig Tissue: The experimental results are shown in **Fig.7**. The upward and downward Z-axis movement is shown Fig.7. The biopsy needle injecting and ejecting experiment is performed four times on the tissue. During injecting or ejecting on the different places of pig tissue, we have got maximum injecting force about -6.0 N and ejecting is about 2.5 N. In this experiment the insertion forces are shown in negative region and extraction force on positive. According to the force amplitude the force feedback element is calculated and transferred to the master handheld manipulator. This force amplitude multiplied by the stiffness factor is transferred to master device. The master device user feels the high stiffness during slave injecting and low stiffness during ejecting as shown in **(Fig 7)**.

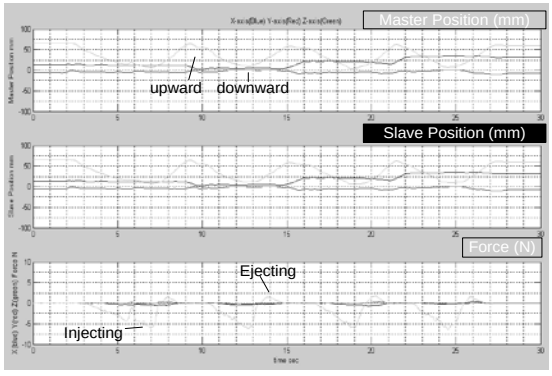


Fig.7: FS Experimental Results on Pig tissue

3.4 Experimental result on Beef Tissue: The experimental results are shown in **(Fig 8)**. The first graph is about master positioning in millimeter (mm) with all axes. The upward and downward Z-axis movement is shown Fig 8. The biopsy needle injecting and ejecting experiment is performed four times in this experiment. During injecting or ejecting on the different places of beef tissue, we have got force in the range of -7.0 to 1.5 N. The injection force is little higher than pig tissue due to the stiffness of the material. According to the force amplitude the force feedback element is calculated and transferred to the master handheld manipulator. This force amplitude multiplied by the stiffness factor and transfer to master device.

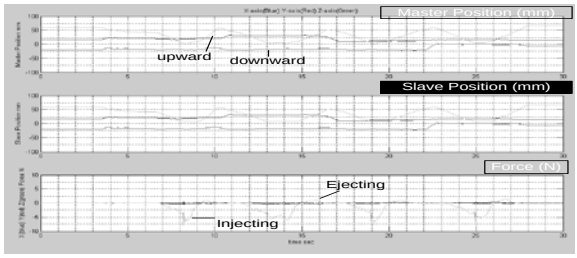


Fig.8. FS Experimental Results on Beef Tissue

3.5 Experimental result on Chicken Tissue: The biopsy needle injecting and ejecting experiment is performed seven times. During injecting or ejecting on the different places of the chicken tissue, the maximum range of force -7.5 to 1.0 N is achieved. In this experiment the injection forces are shown in -ve region and ejecting force on +ve. The results are little changed from pig or beef tissue. This force amplitude is multiplied by the stiffness factor and transfer to master device. The master device user feels the force feedback on master device during slave injecting and ejecting. This time force feedback sensation is little harder than before as shown in **(Fig.9).**

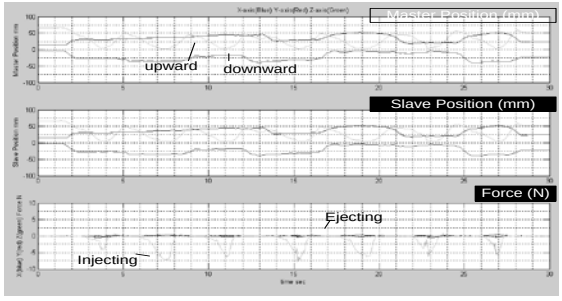


Fig .9. FS Experimental Results on Chicken tissue

5.6 Experimental result on Rubber Foam: The experimental results are shown in **Fig.10**. The first graph is about master positioning in millimeter (mm) with all axes. The upward and downward Z-axis

movement is shown in green. The biopsy needle injecting and ejecting experiment is performed five times. During injecting or ejecting on the different places of foam, we have got force in the maximum range of -4.5 to 1.0 N. The results are not same as per pig, beef and chicken tissue due to different mechanical property. This time needle injecting has low stiffness than before as shown in (**Fig 10)**.

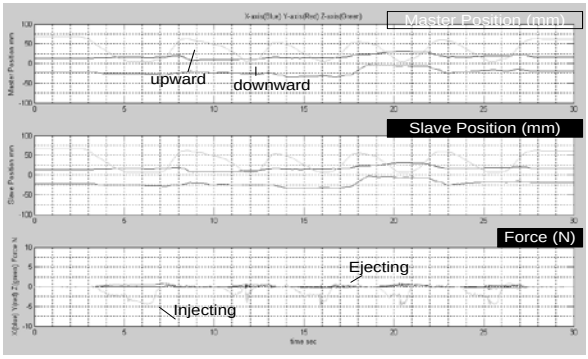


Fig .10. FS Experimental Results on Rubber Foam

Statistical data about the force sensor (FS) on different tissues is shown in **(Table. I).**

Table I. FS statistical data during needle insertion/extraction

(FS)	Free	Beef	Pig	Chicken	Rubber foam
Min	-0.3347	-7.916	-6.365	-7.901	-5.45
Max	0.334	1.458	1.835	0.8063	0.8513
Mean	0.0001544	-0.9583	-1.287	-1.135	-0.8327
Median	-0.0003193	-0.07851	-0.1559	-0.1219	-0.09625
Mode	-0.008739	-0.1055	-0.1227	-0.07743	-0.05994
Std	0.06595	1.81	2.056	1.894	1.324
Range	0.6688	9.374	8.2	8.707	6.302

4. CONCLUSION

This paper is presented a master slave proposed 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 by using force sensor.

5. ACKNOWLEDGEMENTS

This work was supported by the National High Technology Research and Development program of CHINA (863 Project) under the Grant No. 2011AA040201, 111 project under the grant No. B08043, National Science Foundation For Distinguished Young School Grant No.60925014 and Mehran University Engineering and Technology Jamshoro, Pakistan.

REFERENCES:

Dombre, E., G. Duchemin, P. Poignet, and F. Pierrot, (2003) 'Dermarob: a safe robot for reconstructive surgery', Robotics and Automation, IEEE Transactions on, vol. 19, No. (5), 876-884.

King, C. H., M. O. Culjat, M. L. Franco, C. E. Lewis, E. P. Dutson, W. S. Grundfest, and J. W. Bisley, (2009).'Tactile feedback induces reduced grasping force in robot-assisted surgery', IEEE transactions on Haptics, vol. 2, No. (2), 103-110,

Mahvash, M., and A. Okamura, (2007) 'Friction compensation for enhancing transparency of a teleoperator with compliant transmission', Robotics, IEEE Transactions on, vol. 23, No. (6), 1240-1246,

Masamune, K., G. Fichtinger, A. Patriciu, R. C. Susil, R.H. Taylor, L.R. Kavoussi, J.H. Anderson, I. Sakuma, T. Dohi, and D.Stoianovici, (2001) 'System for robotically assisted percutaneous procedures with computed tomography guidance', Computer Aided Surgery, vol. 6, No. (6), 370-383.

Rossi, A., A. Trevisani, and V. Zanotto, (2005) 'A telerobotic haptic system for minimally invasive stereotactic neurosurgery', The International Journal of Medical Robotics and Computer Assisted Surgery, vol. 1, No. (2), 64-75.

Syed, A. A., X.G. Duan, A. N. Khizer, M. Mengli, X. Kong, and Q. Huang, (2014) Design and Implementation of Probe Driver Teleoperative Force Feedback System', TELKOMNIKA Indonesian Journal of Electrical Engineering, vol. 12, No. (6) 923-928.

Syed, A.A., X.G. Duan, A. N. Khizer, M. Mengli, X. Kong, and Q. Huang, (2013) 'Maxillofacial surgical robotic manipulator controlled by haptic device with force feedback'. Proc. Complex Medical Engineering (CME), ICME International Conference on, 363-368.