Development of a Real-Time Simulink Based Robotic System to Study Force Feedback Mechanism during Instrument-Object Interaction

Jaydip M. Desai, Antonio Valdevit, Arthur Ritter

Abstract—Robotic surgery is used to enhance minimally invasive surgical procedure. It provides greater degree of freedom for surgical tools but lacks of haptic feedback system to provide sense of touch to the surgeon. Surgical robots work on master-slave operation, where user is a master and robotic arms are the slaves. Current, surgical robots provide precise control of the surgical tools, but heavily rely on visual feedback, which sometimes cause damage to the inner organs. The goal of this research was to design and develop a real-time Simulink based robotic system to study force feedback mechanism during instrument-object interaction. Setup includes three VelmexXSlide assembly (XYZ Stage) for three dimensional movement, an end effector assembly for forceps, electronic circuit for four strain gages, two Novint Falcon 3D gaming controllers, microcontroller board with linear actuators, MATLAB and Simulink toolboxes. Strain gages were calibrated using Imada Digital Force Gauge device and tested with a hard-core wire to measure instrument-object interaction in the range of 0-35N. Designed Simulink model successfully acquires 3D coordinates from two Novint Falcon controllers and transfer coordinates to the XYZ stage and forceps. Simulink model also reads strain gages signal through 10-bit analog to digital converter resolution of a microcontroller assembly in real time, converts voltage into force and feedback the output signals to the Novint Falcon controller for force feedback mechanism. Experimental setup allows user to change forward kinematics algorithms to achieve the best-desired movement of the XYZ stage and forceps. This project combines haptic technology with surgical robot to provide sense of touch to the user controlling forceps through machine-computer interface.

Keywords—Haptic feedback, MATLAB, Simulink, Strain Gage, Surgical Robot.

I. INTRODUCTION

SURGICAL robots are computer-controlled manipulator using controller, robot base and surgical tools with imaging system. It offers exceptional control and precision of surgical instruments. Surgeon uses a computer console to manipulate the instruments attached to multiple robotic arms. The computer translates and sends the surgeon's movement to the robotic arms. Robotic surgery is used in Minimally Invasive Surgery (MIS) for bladder cancer, mitral valve prolapse, colorectal cancer, obesity, coronary artery disease, prostate cancer, throat cancer, thyroid cancer, uterine fibroids, kidney disorders, kidney cancer, gynecologic cancer and uterine prolapse [1], [2]. The advantages of robotic surgery include less pain, less bleeding, less risk of complications, shorter duration of hospital stay and faster recovery [3], [4]. It does have lack of haptic feedback, which may cause human error and damages organ/tissue during MIS [5]-[7].

II. LITERATURE REVIEW

Surgical robot consists of a robot base with four arms, a 3D stereoscopic camera for imaging and interface cart to transfer joints movement from master to slave operation. Current surgical robots provide exceptionally well-controlled unit with stereoscopic view but does not provide force feedback mechanism to the surgeon. All surgeries are performed through human-machine interface. Various studies on robotic surgical unit described the lack of haptic feedback in MIS, which can cause intra-operative injury [8]. Researchers have used different techniques to provide sense of touch ability to the surgeon uses robotic surgical unit, which includes use of tactile and or force sensors with direct/indirect force measurement. There are two types of force sensing methods used in surgical robots for force feedback mechanism. First method is to use force sensing circuitry at the jaws of the existing surgical instruments [9], [10] whereas second method uses design and development of microelectromechanical system based force sensor to detect force applied on tissue/organs when the instrument-tissue interaction occurs [11]-[13]. Preliminary study on visual sensory substitution permits the surgeon to provide precise and greater tension of surgical knot tying [14]. Surgical robots are very expensive and it's very difficult to combine haptic technology algorithm with the controller unit of current surgical robots and that's why this research project was hypothesized to develop a Simulink based real-time robotic system to control forceps using Novint Falcon haptic feedback controller. It is achieved by combining laboratory instruments and engineering software to observe real time signals from a haptic controller, kinematics algorithms to acquire best desired position in 3D space, manipulate forceps through linear actuators, calibrate and test strain gages at the jaws of forceps, calculate force when instrument-object interaction occurs and generate a

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feedback signal for the actuators of the Novint Falcon haptic controller.

III. ROBOTIC SYSTEM WITH HAPTIC FEEDBACK

A. Robot Base

VelmexXSlide assembly is used for positioning of surgical tool. Three XSlide assemblies used as a base of experimental setup (XYZ Stage) and it providesthree-dimensional movement of the surgical tool. Surgical tool assembly mounted on carriage of the XSlide assembly shows in Fig. 1 (a) and VXM stepping motor controllers shows in Fig. 1 (b), which generates signals for the XSlide stepping motors.
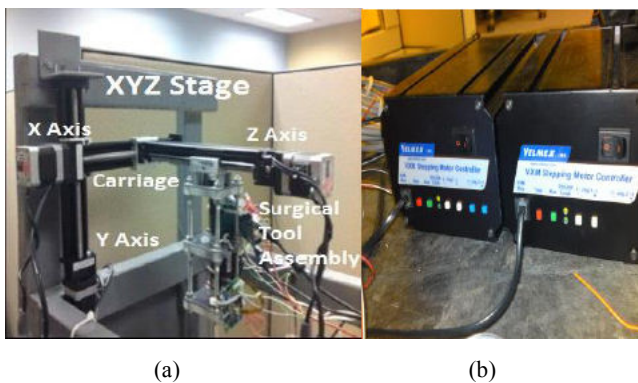

(a)   (b)

Fig. 1 (a) VelmexXSlide assembly (XYZ Stage) and (b) VXM stepping motor controller

B. Haptic Controller

Novint Falcon is a 3D gaming controller, which provides haptic feedback to the user. It is mostly used in gaming where user can feel realistic sense of touch while playing video games. Fig. 2 shows two Novint Falcon controllers used in this research. Novint Falcon provides software that keeps track where the end effector is moved and creates forces that user can feel, by sending currents to the motors are updated 1000 times per second. It gives more realistic sense of touch to the user. Horizontal movement of the end effector is X and vertical movement is Y direction. Z direction includes in and out movement of the Novint Falcon.

Fig. 2 Novint Falcon Haptic Feedback Controller with XYZ Stage

C. Forceps

Forceps is a surgical tool used during the surgery to hold, move or grasp something. Robotic surgical unit provides smooth control of forceps during minimally invasive surgery.

Forceps is connected to the rope, which is used to open and close during robotic surgery. An assembly was designed to hold forceps. Fig. 3 shows surgical tool assembly mounted on XYZ stage. Linear actuators mounted at the top of that assembly, which provides movement of surgical tool and controls its opening and closing.
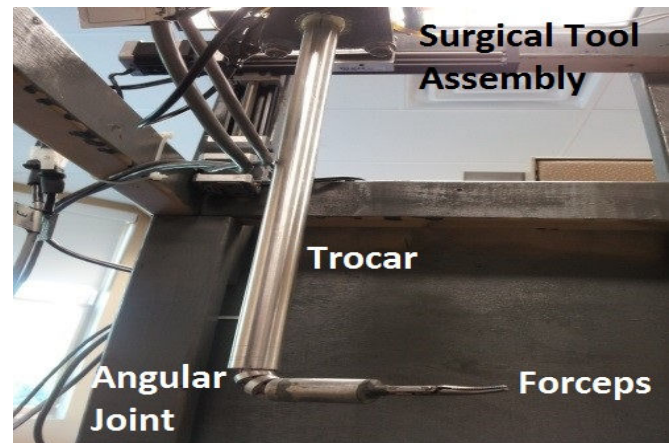

Fig. 3 Surgical tool mounted on XYZ Stage

D. MATLAB and Simulink

MATLAB and Simulink toolboxes were used to design a real-time communication model between Novint Falcon controller and surgical robot. MATLAB programming was used to develop a MATLAB script to control surgical robot base using XSlide Stepping Motor Assembly. Simulink model was designed to communicate with microcontroller and strain gage circuit. Current experimental setup used MATLAB and Simulink models as a central processing unit to provide force feedback to the user controlling surgical setup through haptic feedback controller.

E. Firgelli Linear Actuators a Controller Board

Three PQ-12 Firgelli linear actuators with controller board were placed on surgical tool assembly. Fig. 4 shows PQ-12 linear actuator with controller board used in current setup. These linear actuators were connected to the forceps using plastic ropes, which provides horizontal, vertical and open/close movements to forceps.

Fig. 4 Firgelli PQ-12 linear actuator and controller board

F. Microcontroller

Arduino Duemilanove microcontroller communicates with Simulink in real time using Arduino Simulink library. It

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generates control signal to the Firgelli linear actuator board for the movement of forceps and converts analog signals from strain gages amplifier circuit to digital using 10 bit ADC for further signal processing in Simulink to calculate amount of force applied on forceps jaws.

IV. EXPERIMENT

Experiment used to study force analysis on forceps' jaws when instrument-object interaction occurs using robotic surgical unit. Experimental setup used real time communication using hardware, software and control system. Master-slave operation was designed to control surgical robot base and surgical tool through haptic feedback controller.

Strain gages were mounted on inner and outer jaws' of forceps to detect forces applied on it.

A. Experimental Setup

Fig. 5 displays experimental setup used for haptic feedback mechanism. It includes two Novint Falcon haptic controller units as a master and XYZ Stage &surgical tool assembly with forceps as a slave device. Haptic controllers are connected to computer through usb. MATLAB & Simulink software used to control surgical robot using forward kinematics algorithms. Robotic surgical base is made up with three XSlide stepping motor assemblies. Forceps used as end effector to achieve best-desired task such as grasp or pull an object.
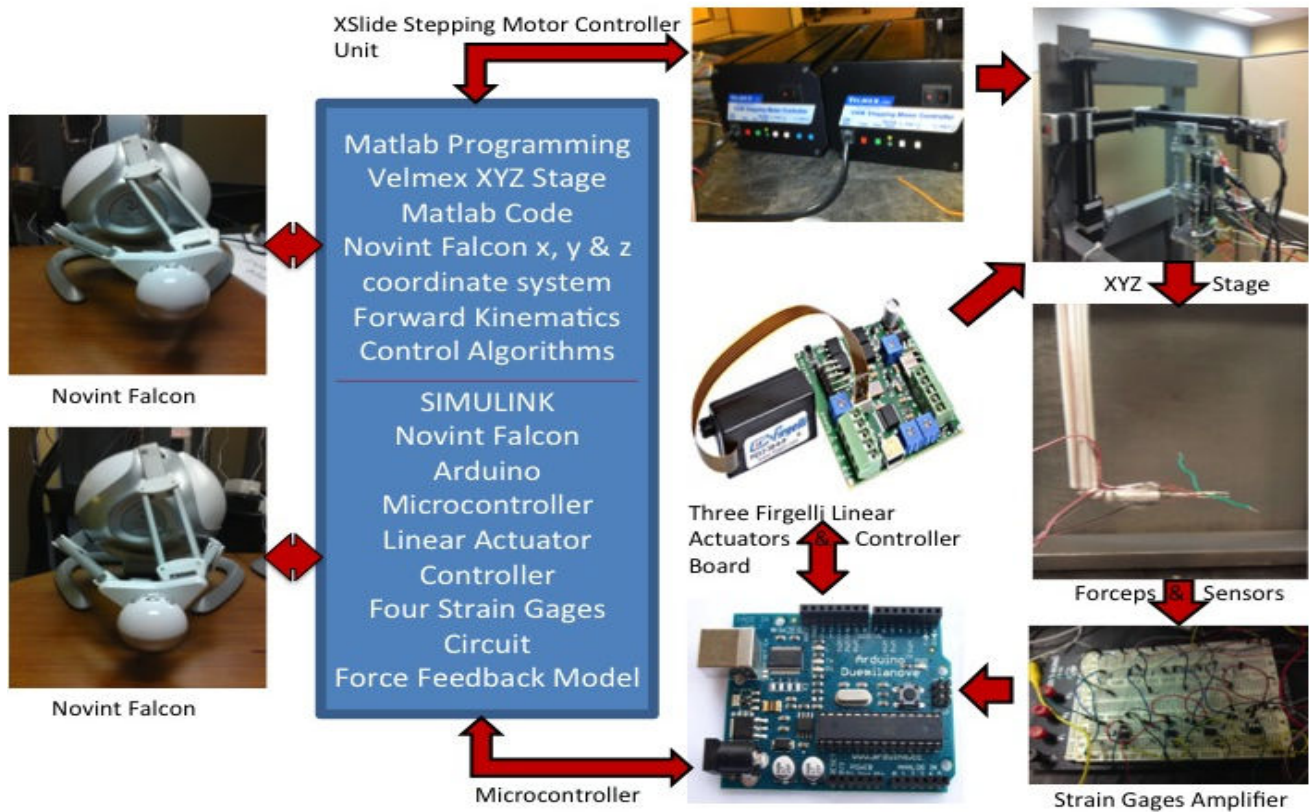

Fig. 5 Experimental setup for haptic feedback mechanism in real time

First Novint Falcon haptic controller used with MATLAB programming to control surgical robot base and second Novint Falcon haptic controller used to control the movement of surgical tool. Forceps mounted on surgical tool assembly. Plastic ropes were used inside trocar to connect with forceps. Three linear actuators were mounted on surgical robot base to push, pull or rotate forceps. Kinematics algorithms were designed to provide precise control of forceps and surgical tool base. Strain gages were mounted on forceps' jaws to sense instrument-object interaction force. Feedback circuit includes amplifier circuit for strain gages and microcontroller board to fed data into the Simulink model to calculate force.

B. Master-Slave Operation

Robotic surgical unit is a master-slave operation. Fig. 6 displays master-slave operation of the project. Two master devices are Novint Falcon gaming controller successfully communicated with haptic library through QUARC software. One Novint Falcon controller used with haptic library, which provides real-time communication with MATLAB programming whereas second Novint Falcon used with QUARC software to create a Simulink model. MATLAB programming script was developed to control XYZ stage of the surgical robot to achieve best-desired position of the forceps in three-dimensional space. Simulink model was able to control forceps through Arduino Duemilanove microcontroller, Firgelli linear actuators and controller board.

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Forward kinematics algorithms used to control the movement of XYZ stage and forceps. Four strain gages were mounted on the inner and outer jaws of forceps to acquire instrument object interaction force. Wheatstone-bridge circuit with single op-amp amplifier used to amplify strain gages signals. Four

10-bit analog to digital converter were able to fed amplified strain gages signal into Simulink model for force measurement. QUARC software library is used with Simulink model to provide force feedback to the user's hand using Novint Falcon haptic feedback controller.
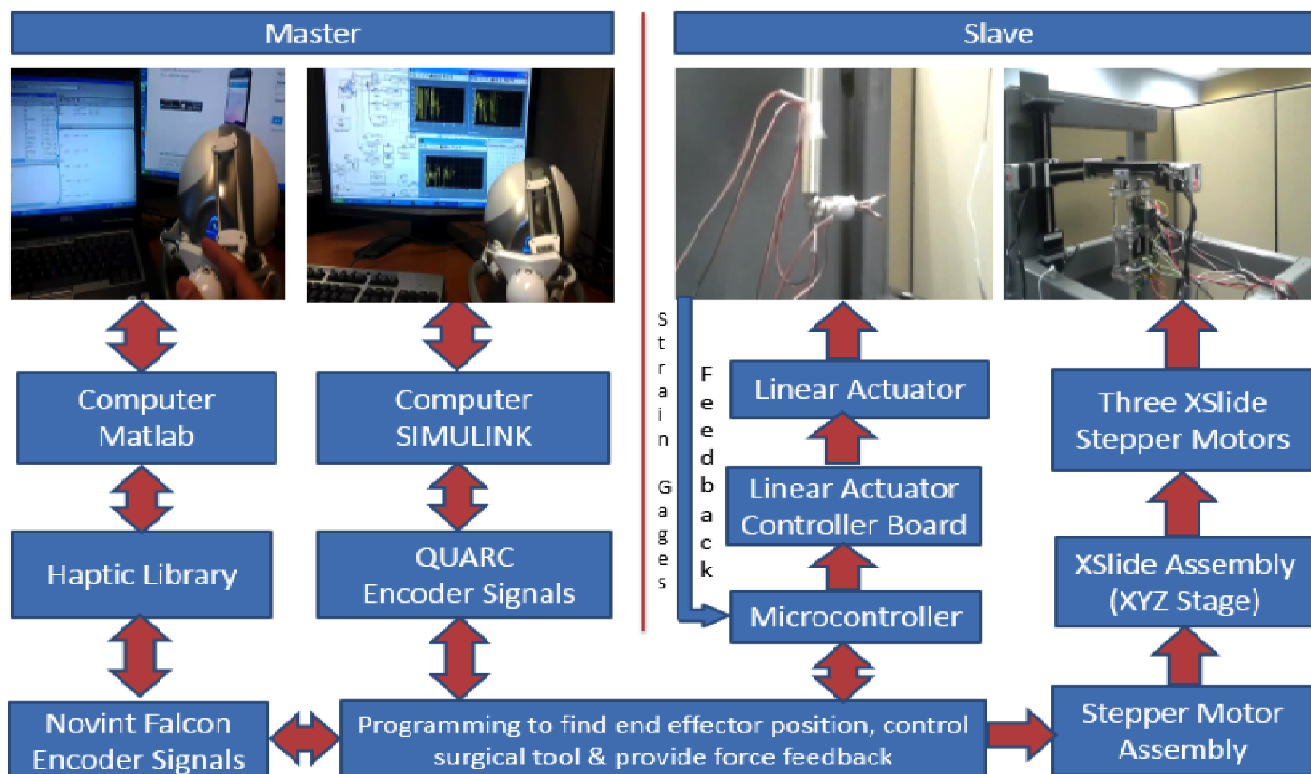

Fig. 6 Master-Slave operation for current robotic surgical setup using two Novint Falcon controllers

C. Surgical Tool– Forceps as End Effector

Forceps is a surgical tool used during the surgery to hold, grasp or move an object. Forceps is connected to the trocar using angular joint. Trocar has plastic tube inside it, which carries plastic wires from linear actuator to forceps. Strain gages were mounted on inner and outer jaws of forceps to detect forces. Fig. 7 shows strain gages placement on forceps' jaws. Inner strain gages were used to detect forces when a forceps holds an object whereas outer strain gages were used to detect forces when a forceps pushes an object.
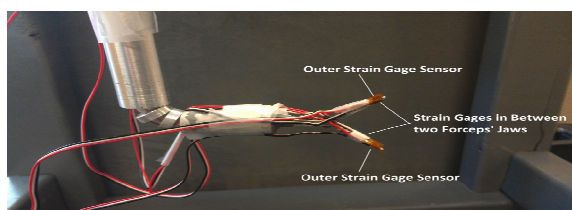

Fig. 7 Strain gages placement on surgical tool

V. Results And Discussion

Current surgical setup is able to detect forces when instrument-object interaction occurs. Two force feedback

controllers were used forward kinematics algorithm to manipulate XYZ base and forceps through MATLAB and Simulink using microcontroller assembly. Strain gages first calibrated using Imada Digital Force Gauge device and then tested with a hardcore wire through haptic feedback controller. Simulink model was designed to read amplified signals from strain gages through Arduino library in Simulink.

A. Real Time Strain Gages Signal from Forceps

Robotic surgical setup used four strain gages, mounted on two inner and outer jaws of forceps. Inner strain gages were used to grasp an object and outer strain gages were used to push/pull operation. Four strain gages were calibrated using IMADA digital force gauge. Strain gages output signal were amplified and then recorded using DI-148U data acquisition system at 240 sampling frequency for a graph. Output signals were converted from voltage to force and samples to time. Fig. 8 shows recorded signals from strain gages using ImadaDigital Force Gauge device by applying various pounds for testing.
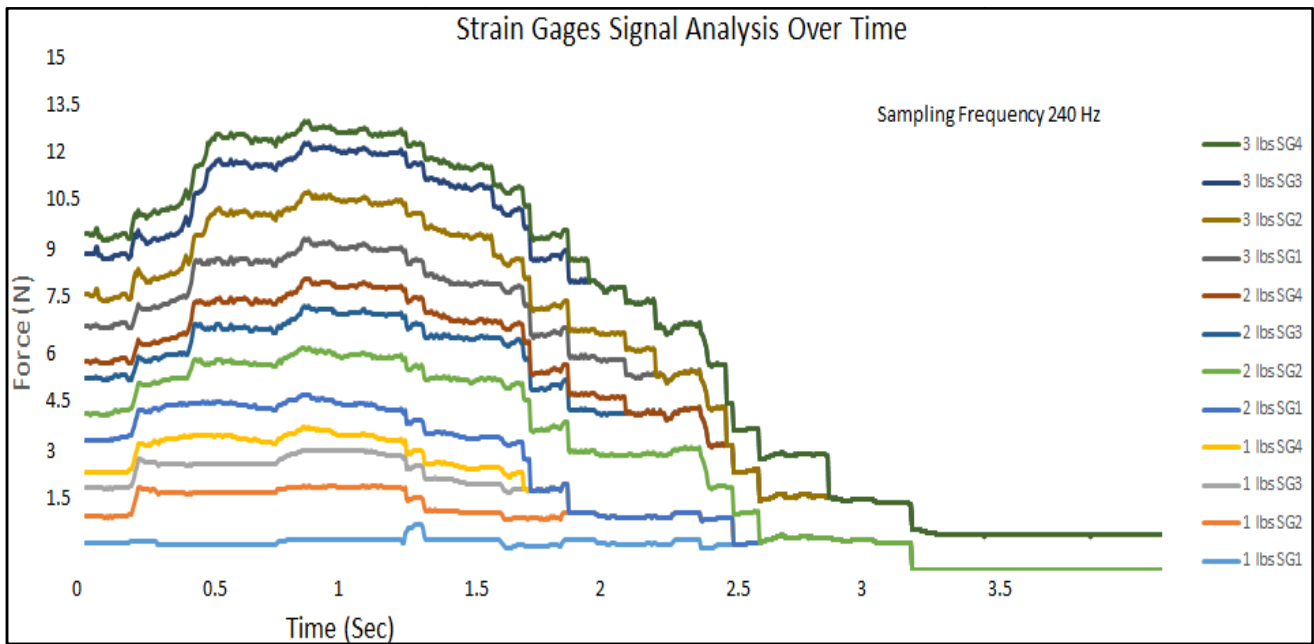
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Fig. 8 Strain gages recorded signals using Imada digital force gauge device – Force vs. Time Curve

B. Strain Gages Signal Analysis

Fig. 9 (a) shows a forceps grasps a hardcore wire and (b) displays Force versus Time waveform when forceps grabs a hardcore wire. Strain gages from inner jaws' of forceps measured strain when forceps grabs it. The signal was then amplified using Wheatstone-Bridge Circuit followed by a single op-amp amplifier. DATAQ DI-148U data acquisition device was used at 240 samples/second to record a signal from forceps' jaw holding a hardcore wire. Signal shows amount of load applied on a hardcore wire when forceps grabs it. Simulink model then uses force values to provide feedback to the user's hand through Novint Falcon haptic feedback controller.
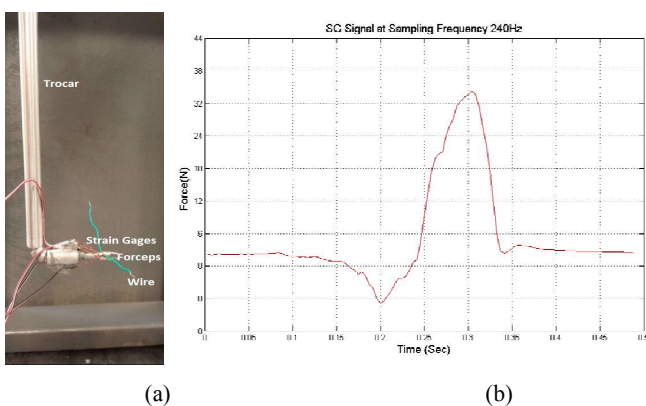
measured using direct-force sensing method during surgical tool movement using current robotic surgical setup. Forces applied on strain gages were in the range of 0 to 35N. Forceps was successfully controlled through Novint Falcon controller using designed simulink model. Simulink model successfully reads strain gages signal and process it through the control system, which calculates forces and provides force feedback to the user. Result on force analysis shows greater application of combining haptic technology with strain gages in medical robotics to provide sense of touch to the user controlling robotic surgical unit. The integrated hardware-software setup can be used to test MEMS based surgical tools and train surgeons in virtual surgical environment to provide haptic feedback using physical-virtual world communication.

(a)   (b)

Fig. 9 (a) Forceps grasps a wire and (b) Real time signal analysis for force feedback mechanism using inner strain gages of the forceps' jaws

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VI. CONCLUSION AND FUTURE WORK

Strain gage technology successfully used to acquire forces when instrument-object interaction occurs. Forces are

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