Development of A Bone Reaming System Using Micro Sensors For Internet Force-feedback Control

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Abstract: - Internal fixation is a widely used treatment method to repair bone fracture, which is one of the most common orthopedic trauma. However, in reaming of the intramedullary canal to facilitate insertion of a guiding rod by creating a surgical passage, severe disturbances such as increased local cortical temperature and elevation of intramedullary pressure can occur. These disturbances have resulted in fatal complications of heart and lungs of the patients. In this paper, we will report on our developmental progress of a re-engineered bone reaming system packaged with MEMS sensors and signal conditioning circuits capable of feeding pressure and temperature information back to a physician for force-feedback control. The final system will also include force-feedback control over the Internet, which will make tele-surgery possible for these bone-reaming procedures. This new system is very important in two aspects: 1) it will allow physicians to drill just one instead of the currently required minimal of two holes in the fractured bone; 2) it allows physicians to have a force-feedback control, which prevents over-pressurization or over-heating of the bone cavity, using existing bone drilling equipment. We believe that, by merging MEMS and tele-robotic technologies for this medical application, we will dramatically improve the safety and time consumed for the internal fixation procures.

Key Words: - Internet control, force-feedback control, micro sensor packaging, MEMS sensors.

1 Introduction

Diaphyseal fractures of the long bone are very common in orthopaedic trauma. Treatment methods include closed reduction and casting, skeletal traction, external fixation, and internal fixation [1]. Internal fixation is achieved by intramedullary nailing, and is the preferred treatment because it can enhance the stability of the intramedullary fixation and shorten the disability time of patients.

Reaming of the intramedullary cavity (bone cavity) is a common operative procedure for intramedullary fixation. Reaming enlarges the medullary canal by removing the inner cortical bone. It can facilitate the insertion of a larger nail, which can increase mechanical stability of the bone structure, by creating a surgical passage for the nail. Reaming can also provide a better fitting by increasing the contact area between the nail and medullary canal.

However, when the reamer drives into the medullary canal, the action is like a piston pushing into a cylinder, and can cause several adverse effects in the medullary canal including disturbance of intramedullary circulation, production of heat and increased intramedullary pressure. A pressure of 300mmHg was recorded in rabbit-object testing, and around 800mmHg in goat experiment [2]. The significantly high pressure would push fat content in bone marrow into blood stream. This causes serious problem if the fat is transported along blood vessel to patient’s heart and lung and the patient suffers from fat embolism. When the fat embolism syndrome occurs in post-traumatized patients, the mortality rate is very high. Therefore, a novel system to monitor patient’s bio-condition is critical and necessary.

Currently, pressure inside the intramedullary cavity is monitored by inserting pressure sensors (typically about 1cm diameter and 5cm length) into additionally drilled holes at the circumferential wall of the fractured bones see (Figure 1). These additional holes not only weaken the bone structure mechanically, but cause additional complexity for the internal fixation surgical procedures. The main aim of our project is to eliminate the additional drilling of holes for sensor insertion by packaging MEMS pressure sensors into the guide rod used for guiding drill bits during the intramedullary canal boring. In addition, an integrated temperature sensor will be packaged to monitor the temperature of the guide rod, and a thermal couple will be used to monitor the bone marrow temperature. Moreover,
information provided by the pressure and temperature sensors will be used by physicians to have a force-feedback control of the drilling equipment. This will minimize the chance of increasing pressure and temperature excessively in the intramedullary canal, which can result in fatal complications. We are also implementing a force-feedback control technique to allow physicians to tele-operate this new system over the Internet, and have demonstrated that controlling and feeding force information is possible in real time even at a distance spanning from Hong Kong to the State of Michigan, USA. The results from all aspects of our development of an Internet tele-operable bone reaming system with force-feedback is reported in this paper.

2 Design of the New Bone Reaming System

In improving the existing system, our fundamental philosophy is that the modifications should have minimal effect or alteration on the existing medical procedures. Giving the dimensions of the components needed for the internal fixation procedures, we proposed to package MEMS sensors into the head section of the guiding rod. This modification will allow the new sensing system to be integrated with the drilling system, and hence, eliminate the need to drill additional holes on the bone structure. Moreover, this implementation will not add any additional medical procedures to the existing ones. Three basic engineering challenges need to be overcome before the new system can be realized: 1) package multiple sensors into a small volume (MEMS technology is essential here); 2) designing a relatively long and hollow mechanical structure with small radius, and able to handle the same load as the existing guide rod; 3) sending power to and receiving signal from sensors embedded in a rotating mechanical structure. Our solutions to these challenges are presented below.

2.1 Conventional System

The existing bone reaming operation system is illustrated in Figure 1. A long medical drill (not shown in illustration) with a hole in the center goes into the bone cavity by using the guide rod as a guid. Physicians can control the depth and drilling direction of the drill by manipulating the guide rod. The push-forward motion of the medical drill raises the bone marrow pressure similar to the piston-pushing effect. Currently, separate pressure-measuring devices are implemented by drilling other holes into the bone to monitor any change on the bone marrow pressure. The surgeon would temporarily stop the operation until the pressure drops back to safety level. The extra holes necessary for pressure sensors would cause additional and undesired damage to the patient’s bone structure.

![Figure 1](image1.png)

**Figure 1.** Reamer drill is pushed into bone cavity to enlarge volume for intramedullary nailing. A guide rod is used to guide the reamer-drill's direction.

2.2 New Reaming System with MEMS Sensors

The proposed new system is shown in Figure 2. This new system, which has almost the same shape and physical dimensions as the existing guide rod, will allow doctors to use it with existing operation tools, and thus, will permit them to learn how to operate the new system quickly.

![Figure 2](image2.png)

**Figure 2.** New system with same physical features as the existing guide rod is inserted into bone cavity. A close-up view of the head-part, which will contain the micro sensors, of the new guide rod is illustrated in Figure 3. The head-part of the guide rod will also restrict the working depth of the operation drills, and contains the signal conditional circuitry of the micro sensors.
2.2.1 Packaging Design

For feasibility test, a miniature pressure sensor from Entran Devices Inc. will be used. It was calibrated for a pressure range up to 50psi, which is range reported in the actual medical operation conditions [2][3]. A picture of the sensor from Entran Devices is shown in Figure 4. It is cased in a stainless steel body, and was chosen for this research project because its capability of working in fluidic environment and miniature size.

The longitudinal and cross-sectional views of the hollow head-part of the new guide rod are shown in Figure 5 and Figure 6, respectively. In Figure 5, the left-most T-shaped channel is the opening and passage for bone marrow pressure measurement. The MEMS pressure sensor is positioned and the end of the T-channel and points its thin stainless steel diaphragm towards the channel. The sensor is adhered by some waterproof epoxy in its suitable position. The epoxy should be applied with a safe distance away from the sensing end. It is to ensure the hardening process of epoxy would not affect the performance of the sensor. Behind the MEMS sensor, a chamber is designed for implantation of the sensor’s factory-made conditioning module and our designed circuit module on PCB with functions of stable voltage supply and primary signal conditioning.

2.2.2 Electrical Signal Output

A special rotating-bearing signal-transmission system was designed to obtain electrical signal from the sensors in the rotating rod. The important components of the rotating-bearing signal-transmission system are shown in Figure 7. The bearing is specially designed to be without an inner ring. It will fit the rotating shaft and has a flexible roller cage which is suitable for applications where the bearing is installed and removed frequently. The bearing will ease the rotational motion of the guide rod during operation and simultaneously supply electrical power and transmit sensor signals.

Experimental result of the electrical signal transmission from the rotating bearing is shown in Figure 8. The experimental conditions are similar to those during the actual medical operation (rotation speed ~800rpm). In the experimental setup, a steady
electrical voltage signal was passed through a short stainless steel solid rod. The signal was transmitted along the rotating rod body, passing the metallic bearing and then being fed to an oscilloscope. We found that the electrical signals were downgraded somehow by a “switching effect” of the rotating bearing. This is because the rotating bearing had some blinking intervals and the rollers were not in constant contact with the bearing case. However, this problem can be solved by appropriate electronic signal-conditioning filter circuit. The unfiltered and filtered signals are compared in Figure 8.

![Figure 7](image1)

Figure 7. a) Picture of the actual cup bearing. b) Illustration of the interior view of the cup bearing. c) Illustration of the end of the hollow rod which will be connected to the cup bearing.

![Figure 8](image2)

Figure 8. Noisy bearing signal can be low-pass filtered. The upper one is the unfiltered signal transmitted through the bearing system, and the lower one is filtered output signal.

### 2.2.3 Mechanical Analysis for the Guide Rod

The following equations were used to analyze the stresses and deflection of the solid and hollow guide rods. These classical results [5][6] were used as a first order comparison of the relative mechanical characteristics of the rods. The deflection of a rod clamped at one end with applied force \( F \) at the other can be found by:

\[
\delta_{\text{max}} = \frac{FL^3}{3EI_c}
\]

where \( L \) is the length and \( E \) is the Young’s Modulus of the rod. \( I_c \) is the moment of inertia of the bending structure and can be calculated for a solid rod by:

\[
I_c = \frac{\pi r^4}{4}
\]

and a hollow rod by:

\[
I_c = \frac{\pi}{4} \left( r_o^4 - r_i^4 \right)
\]

The axial stress caused by this bending force \( F \) can be calculated for the solid rod by:

\[
\sigma_x = -\frac{My}{I_c}
\]

and the shear stress can be calculated by:

\[
\tau_x = \frac{4F}{3A}
\]

The torsional shear stress for a rod under a torque \( T \) can be calculated by:

\[
\tau_\theta = -\frac{T\theta}{J_c}
\]

where the polar moment of inertia \( J_c \) for a solid rod is:

\[
J_c = \frac{\pi r^4}{2}
\]

and for a hollow beam is:

\[
J_c = \frac{\pi}{2} \left( r_o^4 - r_i^4 \right)
\]

Using \( L = 700\text{mm}, E = 199\text{GPa}, r_{\text{solid}} = 3\text{mm}, r_o = 3\text{mm}, \) and \( r_i = 1\text{mm} \), ratio of the deflection and stresses are compared in Table 1 (for any given \( T \) and \( F \)). A comparison of beam longitudinal stress (Eq. 4) versus applied force (to cause a moment) is given in Figure 9 for both hollow and solid beams over the range of current operational range. Since the yield stress for steel is 434Mpa [4], the hollow rod will not cause structural failure within the existing operational force range (assuming a physician will exert equivalent force of \( \frac{1}{4} \) of the average human body weight to bend the rod, or ~200N). Therefore, we believe the hollow rod will be mechanically safe to perform the operation as well as the solid guide rod.
### Stress/Deflection Ratio (hollow/solid)

<table>
<thead>
<tr>
<th>Stress/Deflection</th>
<th>Ratio (hollow/solid)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bending stress</td>
<td>1.52</td>
</tr>
<tr>
<td>Shear Stress</td>
<td>1.46</td>
</tr>
<tr>
<td>Torsional Shear Stress</td>
<td>1.011</td>
</tr>
<tr>
<td>Tip deflection</td>
<td>1.013</td>
</tr>
</tbody>
</table>

**Table 1.** Theoretical comparison of the mechanical characteristics of the solid and hollow guide rod.

### Fluid Pressure Analysis

Since the pressure measured by the pressure sensor will come from two components, namely from pushing the guide rod into the bone cavity and from rotating the guide rod in the cavity, a simple study was performed to compare the magnitude of these two components. A Couette Flow (Figure 10) model was used to estimate the radial pressure gradient caused by rotating the guide rod inside the cavity [7]:

\[
\frac{P}{\rho g} - \frac{r^2 \Omega^2}{2g} = \text{constant}
\]

where \(P\) is the pressure inside the bone cavity at a specific radial location \(r\) (see Figure 10), \(\rho\) is the fluid density (assuming bone marrow density is approximately equal to water density of 998kg/m³), \(g\) is the gravitational constant (9.8m/s²), \(\Omega\) is angular velocity of the rotating guide rod (83.78 rad/s or 800rpm). The calculated value for this pressure gradient is 70.3Pa (0.0102psi or 0.53mmHg), corresponding to sensor voltage signal of 0.00796mV and is within the 1% tolerance of the sensor’s reading span or less than 1% of the intended dynamic measurement range. Hence, the radial pressure gradient due to the rotating guide rod can be ignored in real-life experiments.

Figure 9. Theoretical deflection due to applied force for solid and hollow guide rods.

#### 2.2.4 Fluid Pressure Analysis

#### 2.2.5 Calibration of Pressure Sensor

The calibrated results of the Entran Device pressure is given below in Figure 11. The sensor was tested over a range up to 50psi and showed a linear output.

Figure 10. Circular Couette Flow theoretical model of pressure gradient caused between rotating inner component and stationary outer case.

Figure 11. Experimental calibration of the Entran Device fluidic pressure sensor.

### 2.3 Integrated Micro Pressure and Temperature Sensor

We have designed and fabricated a MEMS piezoresistive pressure and temperature-sensing device (Figure 12), which can be packaged into the head-section of the guide rod. Potentially, very complex pressure and temperature sensing elements along with their signal conditioning circuits (including wireless transmission) can be integrated onto a single chip. The design, fabrication, and applications of these piezoresistive sensors can be found in [11].

The CMOS integrated sensor chips were fabricated at the East China Research Institute of...
Optical Electronics using double side polished 3-inch (100) silicon wafers. The doping concentration of the n-type silicon wafers is about $10^{15}/\text{cm}^3$. The piezoresistors were formed by injecting $B^+$ with $5.5 \times 10^{14}/\text{cm}^2$ dose, $100 \mu\text{A}$ beam-current, $40\text{keV}$ for 35 seconds. The junction depths of the piezoresistors were diffused to about $1 \mu\text{m}$ by heating the wafers for 150 minutes under $N_2$ and 20 minutes under $O_2$ at $920^\circ\text{C}$. Standard CMOS process was used to make the detection circuits and the analogue switches.

A backside photolithographic procedure was followed to open etching windows for the membranes. The CMOS circuits were protected and the chips were immersed in a $33\%$ KOH solution at $76^\circ\text{C}$ and time-etched to obtain $70\mu\text{m}$ thick membranes. Finally, the silicon chips were cut to $4 \times 4\text{mm}^2$ sensor dice. These integrated sensors are current under experimental test and calibration for pressure and temperature.

![Figure 12](image)

**Figure 12.** A MEMS integrated pressure and temperature sensor on a 1mmx1mm square chip.

### 3 WWW Sensing of the Micro Sensors and Control of Moving Objects

#### 3.1 Internet Server

In fact, there are many methods for using the Internet to control and sense. We suggest only a simple way to communicate data over the Internet here, and by no means is it an optimal way of performing control and sensing over the Internet. To perform the Internet control, the most convenient way is setting up a World Wide Web (WWW) Server (e.g., use Apache WWW Server 1.3.9, the default sever for Solaris and Linux) and File Transfer Protocol (FTP) Server (e.g., use WAR FTP DAEMON). By using these Internet servers, client can perform the connection by most popular browsers like Netscape and Internet Explorer. However, for a more advanced method, where the WWW server can be eliminated to increase the communication speed, the work of I. Elhajj et al. [13] should be referenced.

Since in network terminologies the words “local server” and “remote client” can be used interchangeably, depending on the perspective of a user, we will give a definition for these words now for clarity. For this paper, we will assume that a bone reaming system is physically connected to a PC housed in the Advanced Microsystems Laboratory (AML) of The Chinese University of Hong Kong, and a joystick is physically connected to a PC housed in the Robotics and Automation Laboratory (RAL) of Michigan State University. So, “local server” is the PC in AML and “remote client” is the PC in RAL. Also, a “web server” is just a generic program that “serves” a PC to be connected to a “web” of PCs (or other communication devices).

#### 3.1.1 World Wide Web Server

WWW server was chosen as the connection medium because of several reasons. Firstly, it supports the Internet Protocol, which is widely used in networking nowadays. Secondly, WWW is the most common and the easiest way for people all over the world to access the Internet. It provides a good Graphical User Interface (GUI), so that the interface can be more user-friendly and client can operate it more easily. Moreover, it provides large compatibility with many computer languages such as Java, Common Gateway Interface (CGI), etc. Also, a web server can be built in different operating systems such as Windows, Linux and Unix.

#### 3.1.2 File Transfer Protocol Server

In order to let a client to observe the image or read visual data in real-time, a FTP Server was built to let image or graphics upload to the server, which allows a client to view them through a commercial browser in real-time. An alternative is to use a video-conference software, which may not be readily available and not able to transmit graphical or numerical data easily. The image can be captured by a CCD camera that is connected to the computer. Actually, there are two different transmission protocols through Internet, one is called TCP/IP and the other one is called UTP/IP. TCP/IP requires a continuous server-client connection, and hence fast computation power. Its performance will also
degrade as the number of clients increase. For this project, we have use the UTP/IP non-connection-based communication protocol, because it requires less computation power has stable performance even with multiple clients.

### 3.2 I/O Interface Software

Since the project involves input and output (I/O) interface for the computer and Internet transmission, number of programming languages, i.e., Microsoft Visual C++, Java, Hyper-Text Markup Language (HTML), were used. Their roles are described below.

#### 3.2.1 Java

Java is an object-oriented programming language and is specifically designed for Internet connection and network. Java can be divided into two types. Java Application, which is a stand-alone program, can be executed directly. Java Applet, on the other hand, usually is a small application and mainly used on the WWW. Java Applet requires an external viewer program like a web browser to run it. In the project, 3 pairs of server-client connection programs were developed to allow signal communication between server and client. For the server side, the program was written in text mode so that it could minimize the computation resource of the server and allow more clients to access it while running more stably. For the client side, Java Applet was chosen so that users can access it by any popular browser with a user-friendly interface.

##### 3.2.1.1 Programs in the Client PC

**Request the applet** -- The remote client web browser requests a Java applet from the local server PC that allows the user interface to be accessible through specified URL.

**Receive the applet** -- The remote browser initiates a separate TCP/IP session to download the applet (treated like any other HTML objects, e.g. an external image).

**Load and execute the applet** -- The web browser loads the applet into the client’s memory, and then executes it. After the client receives a command from a joystick, it sends a signal to the browser at the server (AML).

##### 3.2.1.2 Java Program in the Remote Server

In the AML server, a Java program will run and wait for signal from the RAL client PC. After receiving a signal from the client PC, a data packet is sent to the client to acknowledge the reception of suitable data.

#### 3.2.2 Java Native Interface

Since the Java program in the client needs to call the C++ program in the server, the Java Native Interface (JNI) is used in this part to achieve the objective.

The Java Native Interface (JNI) is the native programming interface which is part of the Java Development Kit (JDK). Writing programs using the JNI allows Java code to run within a Java Virtual Machine (VM) to operate with applications and libraries written in other languages, such as C, C++, and assembly. In addition, the Invocation API allows us to embed the Java Virtual Machine into native applications [6]. Actually, those VC++ program are not a self-executable program because they should run only when Java program request them. And Java native Interface is a method for Java program to call C++ program to execute. In order to use it, the C program is required to be complied as Dynamic Link Library format, so that it acts as a library of Windows system.

#### 3.2.3 HTML

Since clients access the Internet control through WWW, so HTML is required to write the server homepage. Moreover, HTML is compatible with most Internet programming languages like Java, JavaScript and CGI.

#### 3.2.4 Java Development Kit

Since the server will execute different Java programs, a Java Virtual Machine System must exist in the computer. This can be done by installing the Java development Kit (JDK) 1.2.2. Then, the three stand-alone java programs can be executed in the background to wait for signals from remote clients. When a signal is received, Java program will call the C++ program to interface with the AD/DA Controller Card.

#### 3.2.5 Microsoft Visual C++

In order to perform the I/O interface with the AD/DA controller card, VC++ (Visual C++ from Microsoft) is used. Although Borland C++ is able to perform the I/O transmission, it is not fully compatible with Java so that VC++ was chosen. A VC++ program was responsible to calculate the effective value for the controller card after receiving signal from the client. For sensing, a program was used to convert the electrical signal into numerical values before feeding back to the client. The third VC++ program allows the controller card to produce correct wave form to control a moving object.

After compiling the C++ programs, a shared
library is built, which can be loaded and called in the Java programs from the local server. The C++ program will be executed whenever called by the Java program from the local server. The Client can input different motion commands to control a moving object.

3.3 Summary

The schematic diagram for force-feedback control of a bone-reaming system is shown in Figure 13. This implementation assumes that the system can be control by anyone on the WWW using a Java enabled browser. The browser and Java portions of the implementation can be eliminated if one-to-one communication is desired. In this case, C++ programs can be made to communicate directly thru an FTP server using UTP/IP protocol.

4 Internet Sensing and Control Experiments

Some experiments were conducted in using the Internet to transmit micro sensor signal and control moving structures. These experiments are described below.

4.1 Reading Micro Temperature Sensor Information Over the Internet

Micro polysilicon temperature sensors were fabricated using the Cronos Integrated Microsystems MUMPs process. For a description of the process and examples of micro sensors produced using MUMPs process, the work of W. Sun et al. [12] can be referenced. The cross-sectional view of the polysilicon thermal sensor is shown in Figure 14. Basically, it is a polysilicon resistive element suspended above the silicon substrate. A microphotograph of the top view of several sensors are shown in Figure 15. The temperature dependence of typical MUMPs resistive elements is shown in Figure 16, which indicate that the resistance variation with temperature is very linear. We have successfully transmitted the sensor signal over WWW using the implementation shown Figure 13.

Figure 13. Illustration of the final implementation of Internet-controlled bone-reaming system.

Figure 14. Illustration of the cross-sectional view of the temperature sensors.

Figure 15. Micro-photograph of the MUMPs fabricated temperature sensors.
4.2 Event-based Internet Force-feedback Control

Delay in communication links has several effects on the stability and synchronization of teleoperation systems. Even more so when force feedback is included. These effects are resulting from the use of time as the reference variable; therefore, if a non-time based reference is used the system would become immune to delay. This suitable action or motion non-time reference variable is called event. The event-based controller design was first introduced in [14]. Then several studies and applications followed [13]. The planning and control of the traditional time-based and the event-based schemes are shown in Figure 17.

Event based control results in not only stability but also event synchronization. Because of delay, visual feedback does not reflect the current state of the system. Meaning that the operator is most of the time viewing an old state of the system. However, by using event-based control, the force is event synchronized. This implies that the force always reflects the most up to date state of the system making the control more efficient and safe.

4.3 Internet Force-feedback Experimental Results

4.3.1 Experimental Setup

We have developed Polyvinylidene fluoride (PVDF) piezoelectric micro-tips as rate-of-force sensors for tele-micromanipulation force-feedback control of micro-mechanical devices over the Internet [15]. A PVDF micro-tip was used as a sensor for our Internet force-feedback experiment. The tip was about 2.5mm long with about 0.8mm at the triangular base (Figure 18). The output from this sensor is amplified using an inverted amplifier with feedback gain of 50. Its signal is then feed to the 8255 analog-to-digital conversion (ADC) card connected to a PC for signal transmission to the Internet. The sensor experimental setup is shown in Figure 19, which is housed in the Advanced Microsystems Laboratory (AML) of The Chinese University of Hong Kong.

![Figure 18](image-url)  
(a) A single laser-micromachined PVDF tip. Each tick on the scale is 1mm. (b) Interferometric image of the tip in (a).

![Figure 19](image-url)  
Experimental setup of the force-feedback experiment over the Internet.

The sensor tip is currently attached to an x-y computer-control positioning table, which can be control via the Internet by a force reflection joystick.
in the Robotics and Automation Laboratory (RAL) at Michigan State University. The x-y positioning table can be replaced with a computer-controlled drilling system potentially. A cantilever is attached to a vibration drum and has a tip vibration of \(\sim 100\mu m \) to 1mm in the frequency range of 1 to 120 Hz to emulate force fluctuations in a bone cavity. The AML sensor tip position can be manipulated by the RAL joystick to contact the vibrating cantilever. The RAL operator observes the AML tip position using a video-conferencing software. The force of the vibrating cantilever sensed by the tip is sent to RAL via the Internet. Once the force is received the force feedback joystick plays it. After that the operator generates a new movement command to be sent to the sensor via the Internet.

4.3.2 Internet Based Control Results

The experimental results presented here relate to the testing done between Hong Kong and Michigan State. During this experiment the operator (RAL) sends position increment commands and receives force feedback from the sensor (AML). The position increments are sent for both \(x\) and \(y\) axes while the force is sensed only in the \(y\) axis.

To emphasize the delay problem over the Internet, a sample of round trip delay between the operator and the sensor is shown in Figure 20. It is clear that the delay is random with no specific pattern or model. If not dealt with, this delay might cause instabilities and desynchronizations. However, as will be seen in the experimental results, the approach used gave a stable and synchronized system.

Figure 21 shows a plot of the desired position increments in both directions and a plot of the played force with respect to the event. It is clear that the commands are random, which is typical of a teleoperation scenario. This makes approaches based on prediction of forces or virtual forces non-realistic. Therefore, actual force had to be sensed and fed back. Figure 22 presents plots of the force felt by the operator, the force sampled for the sensor and the error between them. As seen the force felt is closely following the one sampled from the sensor. Although this is not occurring at the same time instant, since both plots are with respect to local and not global time, the system is still stable and event synchronized [13]. Despite the random time delay experienced between Hong Kong and Michigan State, the system performance is stable as seen from the error, which is constantly converging to zero and has a small value at all times. This implies that, for the given sampling frequency, the system is transparent. Meaning that in case the operator was controlling the sensor from a local machine a similar force profile would have been experienced.

![Figure 20](image1.png)

**Figure 20.** A sample of round trip delay between Hong Kong and Michigan State.

![Figure 21](image2.png)

**Figure 21.** Plots of the desired position increments and the force felt by the operator.

The haptic feedback, force and video, supplied in this experiment, link and couple the operator to the environment. This coupling increases the efficiency and safety of manipulation at microscopic levels. It is similar to magnifying not only the visual but also the sensing capabilities of the operator. Therefore, the force, which conveys significant information to the operator with minimal overhead, is a desirable form of haptic feedback.
Figure 22. Comparison between the forces felt and the ones sent.

5 Conclusion

The development of a novel bone reaming system using micro sensors for Internet force-feedback teleoperations was described in this paper. Thus far, a new guide rod was designed for rotation signal transmission and pressure sensing with micro sensors. An integrated MEMS pressure and temperature sensor sensing system has also been designed and fabrication and is currently under calibration. An event-based control scheme over the Internet has been found experimentally stable over a telemanipulation distance from Michigan to Hong Kong. The integration of all the components of the reaming system is underway. The final product will improve the existing surgical system dramatically by greatly reduce the over all medical operation time and risk to patients while providing an opportunity for Internet tele-surgery.

ACKNOWLEDGEMENT

This work was funded by the Research Direct Grant (2050173) of The Chinese University of Hong Kong, and the NSF Grants IIS-9796300 and IIS-9796287 of Michigan State University. We would like to thank King, W. C. Lai and Carmen K. M. Fung for their significant contributions in developing the Internet control software for this project.

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