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

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Abstract

The development of a medical surgical tool packaged with micro sensors for transmission of *Supermedia* information over the Internet is described in this paper. We define *Supermedia* as a set of communication media, which encompasses acoustic, force, visual, audio, temperature, tactile, and chemical (e.g., taste an smell) information, and which can be physically experienced by a communicator. In this project, we specifically develop *Supermedia* capability for a bone-reaming system that is used for intramedullary fixation procedure of fractured bone treatments. Thus far, transmission of temperature, force, and pressure information from MEMS sensors over the Internet has been demonstrated. Force-reflective control over the Internet using force information from a micro tip has also been shown. We have also packaged a MEMS pressure sensor inside a bone reaming guide-rod and proved that pressure variations inside a long cavity that simulated the environment inside a bone can be monitored, even with the guide-rod rotating up to 600rpm. This paper describes our experimental methods and gives the experimental results for these accomplishments.

1 Introduction

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 (a pressure of 300mmHg was recorded in rabbit, and around 800mmHg in goat from experimental procedures [1].) The significantly high pressure can push fat content in bone marrow into the blood stream, which causes serious problem if the fat is transported along the blood vessel to a patient's heart and lung; in which case, the patient will suffer from fat embolism. When fat embolism syndrome occurs in post-traumatized patients, the mortality rate is very high.

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. One of 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, integrated temperature sensors will be packaged to monitor the temperature of the guide-rod, and thermal couples will be used to monitor the bone marrow temperature. 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 will allow physicians to have a supermedia-based control during a surgical procedure, which prevents over-pressurization or over-heating of the bone cavity. 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.

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 require any additional medical procedures. 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) design a relatively long and hollow mechanical structure with small radius, which is able to handle the same load as the existing guide-rod; 3) send power to and receive signal from the sensors embedded in a rotating mechanical structure.

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Our solutions to these challenges are presented below.

3 Conventional System

The existing bone reaming operation system is illustrated in Figure 1. A long medical drill with a hole in the center goes into the bone cavity by using a guide-rod as a guide. 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.

3.1 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.

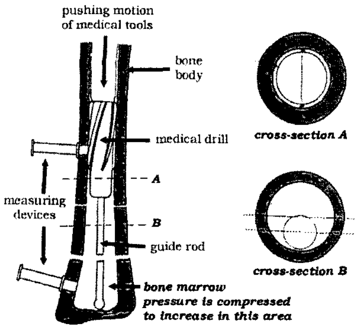


Figure 1. Reamer drill is pushed into bone cavity to enlarge volume for intramedullary nailing. A guide-rod is used to guide the reamer-drill's direction.

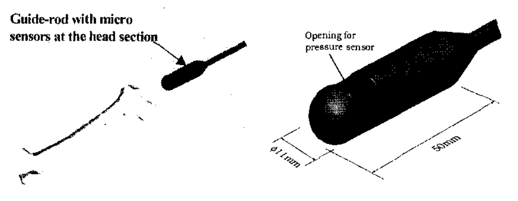


Figure 2. New system with same physical features as the existing guide-rod is inserted into bone cavity.

3.1.1 Packaging Design

For feasibility test, a miniature pressure sensor from Entran Devices Inc. was used. It was calibrated for a pressure range up to 50psi, which is the range reported in the actual medical operation conditions [1][2]. The Entran Devices MEMS piezoresistive pressure sensor is cased in a stainless steel body and was chosen for this project due to its ability to operate in a fluidic environment.

The longitudinal and cross-sectional views of the hollow head-part of the new guide-rod are shown in Figure 3 and Figure 4, respectively. In Figure 3, the left-most T-shaped channel is the opening passage for bone marrow pressure and other supermedia measurements. The MEMS pressure sensor is positioned at the end of the T-channel and has its thin stainless steel diaphragm pointing towards the channel. The sensor is adhered by a waterproof epoxy in a suitable position. Behind the MEMS sensor, a chamber is designed for incorporating the sensor's factory-made conditioning module and our own designed circuit module with functions of voltage stabilization and signal conditioning.

3.1.2 Electrical Signal Output

A special bearing-signal-transmission system was designed to obtain electrical signal from the sensors in the rod. The bearing is designed to be without an inner ring. It fits the rotating rod (3mm outer diameter) and has a flexible roller cage that 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. The design details and the mechanical analyses of the rod are given in [3]. A comparison of the stresses on the redesigned (hollow) rod and the original guide-rod is given in Table 1. It was shown in [3] that all stresses are within the yield limit of the stainless hollow rod.

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

Stress/Deflection	Ratio (hollow/solid)
Bending stress	1.52
Shear Stress	1.46
Torsional Shear Stress	1.011
Tip deflection	1.013

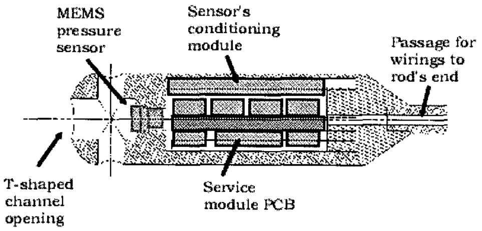


Figure 3. Longitudinal cross section diagram of the new guide-rod's head part. It shows the implanted components.

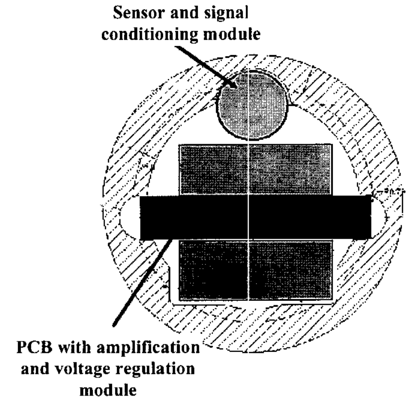


Figure 4. Cross sectional view of service module chamber of guide-rod's head part.

4 Experimental Results of the New Guide-Rod System

Experimental results of transmitting pressure signals from the new guide-rod are presented in this section. Pictures of the actual redesigned guide-rod components are shown in Figure 5 and Figure 6 below. For the prototype test, we packaged only a pressure sensor and its signal conditioning circuit into the guide-rod head (Figure 6). In reality, the current guide-rod head has enough volume to encase other supermedia sensors.

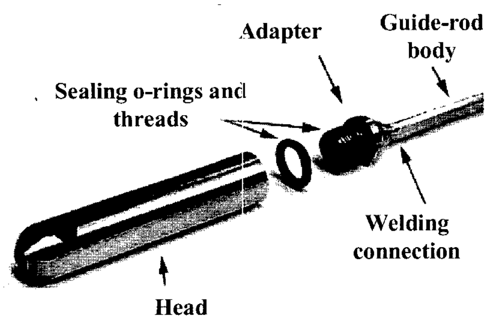


Figure 5. The redesigned guide-rod system.

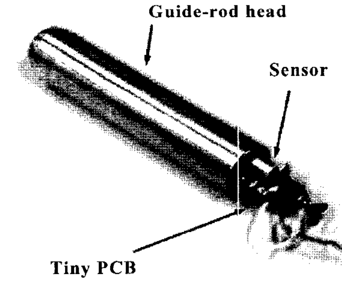


Figure 6. The micro sensor and the signal conditioning circuitry are encased in the guide-rod head.

4.1 Experimental Setup

The guide-rod system was put into a cylindrical pressure vessel as illustrated in Figure 7. An airflow valve was used to control the outflow of air from the vessel. An inlet of the vessel was connected to an air pump such that the pressure inside the vessel can be increased. Controlling the airflow valve can decrease the pressure in the vessel chamber.

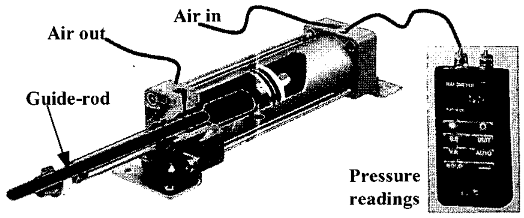


Figure 7. Exposed view of the cylindrical vessel used to simulate environment inside bone cavity.

To simulate the rotating motion of the guide-rod during a bone-reaming operation, a belt-drive system was connected to a rotation motor to rotate the guide-rod. The rotation speed of the guide-rod was measured by an optical encoder packaged with a connection system that read the sensor data during the rotation experiments. The entire experimental setup is shown in Figure 8.

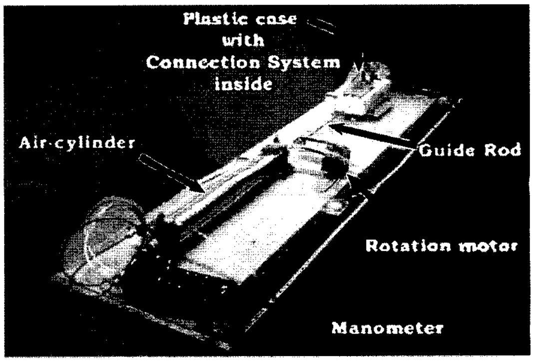


Figure 8. Experimental setup to test pressure variation inside a cylinder vessel using a rotating guide-rod.

4.2 Experimental Results

Since the sensor signal is read using a bearing-transmission system, mechanical contact noises need to be filtered. The low-pass filter shown in Figure 9 was used to process the transmitted signal through the rotating bearings.

In the current system, we have found that the voltage output as a function of pressure is very linear; however, the pressure signal output through the connection system decreases with increasing rotation speed (see Figure 10, Figure 11, and Figure 12).

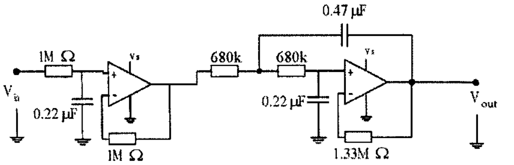


Figure 9. The low-pass filter circuit used to reject mechanical noise due to the rotation bearing.

We have speculated that rotating the guide-rod in a cylindrical cavity may induce Couette flow motion in the vessel [4], and causes drop of pressure as a function of rotation speed. However using Bernoulli's Equation to calculate the change of pressure $\Delta p = \rho r_i^2 \omega_i^2 / 2$ due to rotation at the guide-rod head surface r_i (5.5mm), where ρ is the fluid density (assuming air density of 1.2929kg/m^3), ω_t is the angular velocity of the rotating guide-rod (83.78 rad/s or 800rpm). The calculated value for this pressure gradient is 0.137Pa, which is much less than the 1% tolerance of the sensor's reading span, and hence cannot be detected by the sensor. Therefore, the radial pressure gradient due to the rotating guide-rod cannot be the cause for the observed experimental result. Other possible causes of the output degradation include 1) deflection of the sensor membrane due to centrifugal force and 2) signal rejection by the low-pass filter (Figure 9) at higher rotation speeds. These hypotheses are currently under investigation.

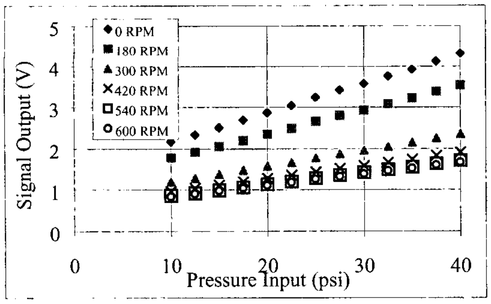


Figure 10. Voltage output versus pressure in the cylindrical vessel; the output also depends on rotation speed of the guide-rod.

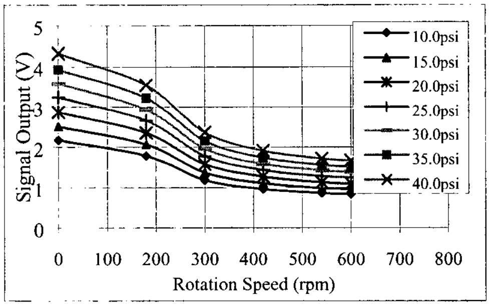


Figure 11. Same data as in Figure 10 except that pressure is used as a parameter in this case.

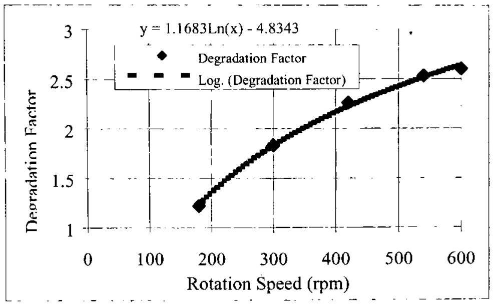


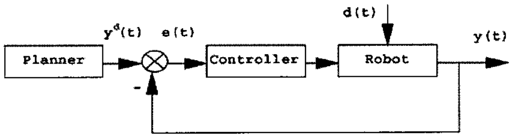
Figure 12. Calibrated degradation factor of the voltage output as a function of the guide-rod rotation speed.

5 Internet Force-Reflection Experiment

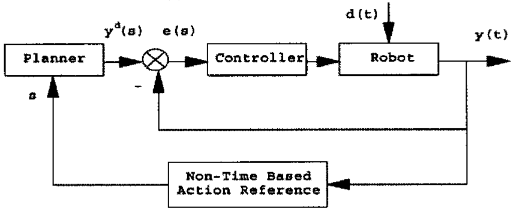
Some experiments were conducted in using the Internet to transmit micro sensor signal, which was then used to perform force-reflective control of an x-y table. Details of these experiments are given in [5], but the results are summarized in the following subsections. We are currently integrating the bone reaming guide-rod system with a force-reflective control system to demonstrate a teleoperated bone surgical system. Eventually, the teleoperated system will also include other supermedia information such as temperature and vision.

5.1 Event-based Internet Force-Reflective Control

Delay in communication links has several effects on the stability and synchronization of teleoperation systems, which is even more prevalent when force feedback is included. These effects are caused by 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 [6], then, several studies and applications followed [7]. The planning and control of the traditional time-based and the event-based schemes are shown in Figure 13.



(a) traditional control



(b) non-time based control

Figure 13. Comparison between traditional time-based and event-based planning and control.

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. By using event-based control, the force is event synchronized, which implies that the force always reflects the most up-to-date state of the system.

5.2 Internet Force-Reflection Experimental Results

5.2.1 Experimental Setup

We have developed Polyvinylidence fluoride (PVDF) piezoelectric micro tips as rate-of-force sensors for force-reflective control, and which can be eventually integrate into many medical tools [5]. The micro tips were laser-micromachined to geometries of 2.5mm long, 0.8mm at the triangular base, and with tip-radii of ~100µm. The output from a PVDF micro-tip sensor was amplified using an inverted amplifier with feedback gain of 50. Its signal was then feed to the 8255 analog-to-digital conversion (ADC) card connected to a PC for signal transmission to the Internet. The sensor tip was attached to an x-y computer-control positioning table which was housed in the Advanced Microsystems Laboratory (AML) of The Chinese University of Hong Kong. The x-y table could be controlled via the Internet by a force-reflection joystick in the Robotics and Automation Laboratory (RAL) at Michigan State University. This x-y positioning table will be replaced with a computer-controlled drilling system eventually. The AML sensor tip position was manipulated by the RAL joystick to contact a vibrating cantilever which vibrated at frequencies from 1 to 120Hz with amplitudes ranging from 100µm to 1mm. The RAL operator observed the AML tip position using a video-conferencing software. The force of the vibrating cantilever sensed by the tip was sent to RAL via the Internet. The force was then received and played by the force-reflective joystick. The operator then generated a new movement command that was sent to move the sensoing tip via the Internet.

5.2.2 Internet-Based Control Results

To emphasize the delay problem over the Internet, a sample of round trip delay between the RAL and AML is shown in Figure 14. It is clear that the delay is random with no specific pattern or model. If not dealt with, this delay might cause instabilities and de-synchronizations. Figure 15 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 16 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 [7]. Despite the random time delay experienced between Hong Kong and Michigan Sate, 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 – in the case that the operator was controlling the sensor from a local machine a similar force profile would have been experienced.

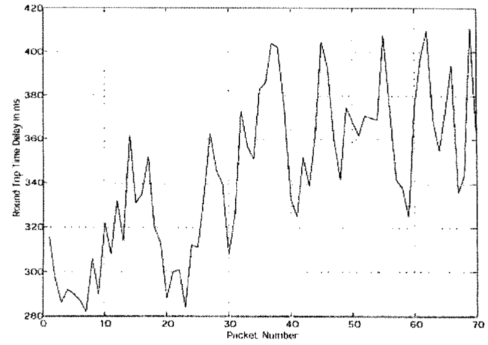


Figure 14. A sample of round trip delay between Hong Kong and Michigan State.

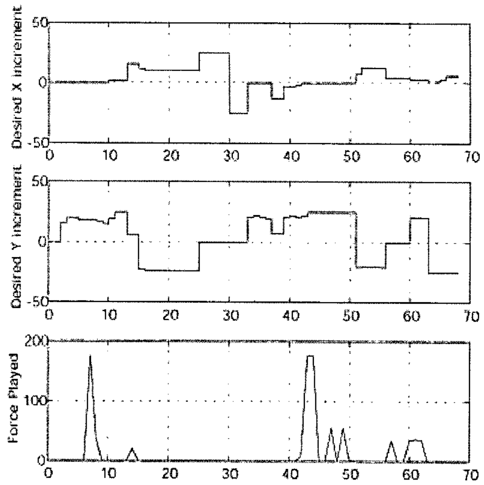


Figure 15. Plots of the desired position increments and the force felt by the operator.

6 Conclusion

The development of a novel bone reaming system using micro sensors for Internet force-reflective teleoperations was described in this paper. A new guide-rod was developed for rotation signal transmission and pressure sensing with a micro sensor. 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 components of the new 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.

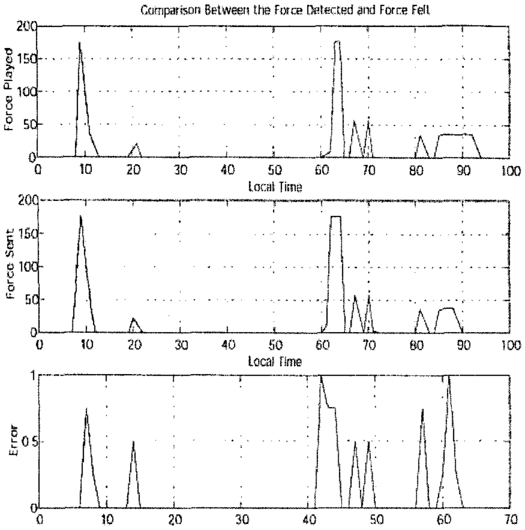


Figure 16. Comparison between the forces felt and the ones sent.

7 Acknowledgement

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