A modular mechatronic system for automatic bone drilling

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Abstract

Drilling tools currently used in surgery depends only on the surgeon’s manual skills to stop the penetration when completing a hole. This paper presents a modular mechatronic system for automatic bone drilling in orthopedic surgery. In extensive drilling tests on real human skulls, there were no unexpected failure, and the overshoots of all tests were well less than 2mm.

摘要

目前外科手術使用之骨骼鑽孔機必須依賴醫師的技巧在鑽孔完畢時停止進給。本論文描述一個用在外科手術自動骨骼鑽孔之模組化機電系統。本系統在以人體頭骨作廣泛鑽孔測試，均能自動鑽穿停止，沒有不預期失效，且所有測試鑽孔過切量均遠小於2mm。
1. Introduction

In surgery, hand-held motor driven tools are used to manually perform bone-machining procedures such as drilling, reaming, and sawing. Currently, bone drilling tools used in surgery do not include any means for the control of penetration. Only the surgeon’s manual skills are used to stop the penetration of the drill when a hole is completed. Allotta et al. [1997] pointed out that the performance of existing motor-driven drilling tools is limited by the lack of any sensing means suitable for recognizing the crossing of interfaces between hard and soft tissues and to discriminate among layers of different tissues.

For this purpose, Allotta et al. [1997] developed a hand-held drilling tool for orthopedic surgery. The main tool feature is the capability of early detection of interfaces between layers of different bone tissues and automatic feed stop according to the specification of the surgeon. A force sensor is embodied in the drilling tool to detect the sharp drop in thrust when the drill crosses the interfaces between hard and soft tissues of the bone. After comparing several methods [Allotta et al., 1996], a fuzzy logic controller is used for controlling penetration.

Baker et al. [1996, 2 papers] also presented a mechatronic drilling tool for precise drilling of flexible bone tissues during ear surgery. By characterizing the tissue from real time drilling data, it is able to control the drilling to complete the break-through with minimum drill bit protrusion. The feed carriage houses the motor, which produces the drilling rotation, and all sensing components that measure axial force and torque on the drill bit and its displacement. A support is used to help steady the hand held tool. Kaburlasos et al. [1997, 1998] further developed a two-level fuzzy-lattice learning scheme for on-line estimation of the thickness of a stapes bone using a force/torque pair of drilling profiles.

Glauser et al. [1991] described a robot dedicated to stereotactic neurosurgery, which consists of the introduction of a small probe with a diameter of 2~3 mm through a hole drilled in the skull, in order to reach a point inside the brain. This point has
previously been located on scanner sections and marked by means of a reference system on the patient’s head. **A motor-driven drilling tool is used to perforate the bone.** In this system, the electric current consumed by drill motor is analyzed. Comparing the electric current to several thresholds, the beginning of drilling, crossing of different layers, and final break-through can be spotted. In this device, **the drill must not penetrate beyond 2 mm inside the skull to prevent injuring the dura.**

**Bouazza-Marouf** et al. [1996] presented a purpose built manipulator for invasive orthopedic surgery. This manipulator allows a drill-bit guide to be automatically aligned with the planned drilling trajectory. The surgeon can then perform manual completion of the drilling stage. **A strain gauge, which monitors the axial drilling force, is incorporated** into the design of the drill-feed carriage to provide force feed back for safety enhancement. Following this work, Ong and Bouazza-Marouf [1998, 1999] described a reliable and repeatable method of break-through detection based on a modified Kalman filter when drilling into long bones. The effects of system compliance and inherent drilling force fluctuation on the profiles of drilling force, drilling force difference between successive samples and drill bit rotational speed, are also taken into consideration.

This paper presents the development of **a modular mechatronic system for automatic bone drilling in surgery.** The development of a “modular system”, rather than a new drilling tool, is emphasized. **One of the major objectives of this research is to develop “add-on” devices that are compatible with current DC motor-driven drills that are commercially available.**

This system has undergone extensive drilling test on real human skulls under various cutting conditions. **There were no unexpected failure, and the overshoots of all drilling tests were well less than 2mm.**
2. The modular architecture of the system

There are three major modules in the system as shown in Figure 1: the control unit, the feed carriage, and the supporting arm.

![Diagram of the system modules](http://designer.mech.yzu.edu.tw/)

**Figure 1. The three modules of the system**

The control unit consists of a control box and a PC. Under the modular design consideration, electric current consumed by the DC motor of the drill while drilling the bone is used as the sensing signal, instead of building force sensors into the drill to measure axial force. A hand-held motor-driven drill can be plugged into the control box, and the surgeon can perform drilling task as usual. The control box supplies power to the drill, and in the mean time, the electric current consumed by the DC motor of the drill is analyzed. This electric current has a direct relation with the cutting torque on the drilled bit.

The control box transfers this electric current into voltage signals. Figure 2 shows a typical plot of time vs. voltage when drilling a piece of human skull. Since a human bone consists of an outer shell of cortical bone around a central mass of cancellous bone, there are two distinct peaks in Figure 2. This pattern is very similar to the figures of time vs. axial force obtained by Bouazza-Marouf et al. [1996], and Allotta.
et al. [1997] when drilling bones. Similar fuzzy control ideas can also be applied to discriminate among layers of different tissues using the variation of the electric current. When break-through (represented by the second peak and a sharp drop) is detected, the power to the drill will be cut and stops drilling.

![Figure 2. Time vs. voltage when drilling human skulls](image)

Using this add-on control unit alone augments the manual skills of surgeons without changing current surgical practice, which should be helpful in gaining initial clinical acceptance.

The surgeon can also choose to clamp the drill on the sliding block of the feed carriage to feed the drill automatically. As shown in Figure 3, the form of this feed carriage is designed to be a hand tool for the surgeon to hold with both hands to perform drilling operation. The surgeon can hold the handle on the left side, and push the strut in front against the skull to steadily support the drill. The weight of our prototype feed carriage is about 1 kg.
forward alone a power screw. T
most industrial robots are too heavy and not suitable for medical use, and the cost for
develop a robotic manipulator with actuators on all joints as the supporting arm because
surgeon can also estimate the thickness of the bone from the three-dimensional image
used for manual feed if necessary.

Finally, the feed carriage can be attached to a supporting arm. We did not choose to
develop a robotic manipulator with actuators on all joints as the supporting arm because
most industrial robots are too heavy and not suitable for medical use, and the cost for
developing such a manipulator will be very high. On the other hand, we realized that
drilling operation needs only one translational degree of freedom, which is already
provided by the feed carriage. The real need for the supporting arm is that its end
effecter (the feed carriage in this case) is able to reach a given point in a given

Figure 3. A drill clamped to a feed carriage

A step motor (400 pulse/rev) drives the sliding block (together with the drill)
forward alone a power screw. The fuzzy controller in the control unit also controls
the feed rate. The normal feed rate is set at 0.5 mm/s. When the second layer of
cortical bone is detected, the feed rate is reduced. When break-through is detected,
the step motor either stops feeding or auto reverses, according to the specification of
the surgeon. There is a rotation handle bar at the back of the step motor, which may be
used for manual feed if necessary.

In our prototype, the maximum feed depth is 60 mm. A potentiometer is built in
the feed carriage to provide the penetration depth of the drill bit in real time. The
surgeon can also estimate the thickness of the bone from the three-dimensional image
obtained by Computerized Tomography (CT), and specify a maximum penetration depth
for safety enhancement.

http://designer.mech.yzu.edu.tw/
angle deftly and conveniently, but not necessarily automatically. After reaching this point, the supporting arm should have enough stiffness to hold the feed carriage securely and steadily during drilling operation. Positioning precision may not be of ultra most concern.

Under these considerations, we choose a universal arm with magnetic base as our supporting arm. This arm is usually used to hold gauges or indicators in experiments, and is commercially available. This arm has 3 joints providing 5 degrees of freedom. The surgeon can manually move the feed carriage to a given point at a given angle, and tighten the joints by simply turning a knob. These joints are held solid by hydraulic force. The arm has an electric magnetic base, which intends to eliminate vibration and movement. The one used in our prototype has holding force of 140kg, and its arm length is 340mm.

Integrating with an optical positioning device, completely automatic bone drilling can be achieved by our system. Brain surgery is usually carefully planned using Computerized Tomography (CT) and Magnetic Resonance Imaging (MRI). Current frameless optical positioning systems can integrate with the 3D image obtained from CT or MRI for image guided surgery. In particular, BrainLab VectorVision currently used in Chang Gung Memorial Hospital, where this project is performed, uses the “passive marker technology.” The two marker spheres on the VectorVision “probe” reflect infrared flashes emitted by the camera-system. The cameras capture the marker reflections and the system converts each marker’s spatial position.

To integrate with VectorVision, 3 registration markers are attached on the feed carriage of our system, as shown in Figure 5. To calibrate this additional instrument, the surgeon simply touches the probe to each registration marker in any order to complete full registration, this instrument can then be used and visualized simultaneously.
3. Drilling tests on human skulls

This system has undergone extensive drilling test on real human skulls under various cutting conditions, using both industrial drills and surgical drills.

Table 1 shows the results of 25 drilling tests on human skulls. First an industrial drill is used in the tests. The radius of the drill bit is 1mm, effective length 20mm, and the speed is 11,500rpm. Both hand-feed mode (13 times) and automatic feed (12 times) mode were used in the tests. There were no unexpected failure, and the overshoots of all drilling tests were well less than 2mm.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Feed rate</th>
<th>Overshoot, mean ± s.d.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auto-feed</td>
<td>0.57mm/s</td>
<td>0.66 ± 0.20 mm</td>
</tr>
<tr>
<td>Hand-feed</td>
<td>0.5~2mm/s</td>
<td>0.66 ± 0.20 mm</td>
</tr>
</tbody>
</table>

A surgical drill is then used in the drilling test. The radius of the drill bit is 1.5mm, and the effective length is 30mm. Three rotational speeds were tried: 15,000rpm, 45,000rpm, and 75,000rpm. Though the electric currents required at different rotational speeds are different, the voltage signal transferred by the control box of the system
exhibits similar drop as in Figure 2 when breaking through the outer shell of the bone. So drill bit break-through were successfully detected in all 3 speeds.

References


