Development of a Skull Drilling System

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Overview of Project

- **Development**
  - Registration, Tool-path Planning and Robot Control System

- **For**
  - Skull drilling (trepanning)
  - Surgical robot with force sensor
Background

- Skull
  - 3 layers
  - Critical nature adjacent structures

![Cross-Section of Head and Brain](image)

- Outer hard bone
- Soft bone
- Inner hard bone
- Dura mater

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Background

- Making burr hole
  - Manual drill
  - Automatic-releasing cranial perforators
    - ACRA-CUT: www.acracut.cut
    - EasyDrill: www.micromar.com
  - Robot
    - Image guided control [Kazanzides 2008]
    - Active constraints control [Yen 2010]
Background

- Complications
  - Plunging
    - Mechanical failure $\rightarrow$ geometric error
      - 65.6% of surveyed neurosurgeons experienced [Timothy 2011]
  - Skull fracture
    - Cutting force error
  - Slant holes
    - Limitation of drilling
Approaches

- **Basic idea**
  - Using {geometric + dynamic} information
    - for robot control

- **Registration**
  - Initial registration
    - Fiducial markers
  - Registration revision
    - Fiducial markers
    - Probe points & CT surface

- **Path planning**
  - Geometry = triangular mesh \(\Leftarrow\) CT image data
  - Probing, Cutting, Finishing

- **Robot control**
  - Path + Cutting(or Tactile) Force
    - Cartesian coordinate system
Robot with Force Sensor

- Neuromate
  - 5-axis robot
- JR3
  - 6-DOF force sensor
Overall Procedure

Main Task:
- Initial registration
- Registration revision #1
- Cutting hard/soft bone
- Registration revision #2
- Cutting inner hard bone

Robot Task:
- Guided motion
- Probing
- Cutting
- Probing
- Poke cycle

CT image
- Fiducial pts
- Outer sf
- Inner sf

Outer hard bone
- Inner soft bone
- Inner hard bone
- Dura mater
Registration

- Initial registration
  - Fiducial marker positions of CT & Robot

- Registration revision
  - Accuracy
    - hole axial direction vs. hole position
  - \{ fiducial markers + mesh \}_CT + \{ fiducial markers + probe points \}_robot

probing pattern
Path Planning

- **Type of path for skull drilling**
  - **Probing path**
    - To collect the surface positions
  - **Cutting path**
    - To remove volume rapidly
  - **Poking path**
    - To finish without damage
  - **Reaming path**
    - To make wide opening
Path Planning / Type of Path

- Probing path
- Cutting path
- Poking path
- Reaming path
Path Planning / Offset Surface

- **Cutter offset point**
  - Cutter center point when the cutter is on the surface
  - \( P_c = P_s + r \mathbf{N} \)
    - \( P_s \): cutter contact point of surface
    - \( r \): cutter radius
    - \( \mathbf{N} \): unit surface normal at \( P_s \)

- **Computing an offset point**
  - Intersection (cutter moving direction) & (offset surface)
  - Projection point on offset surfaces along moving direction
    - Take higher one

- **Offset Surface**
  - \( \{ \text{Offset triangle} + \text{Cylinder} + \text{Sphere} \} \)
Path Planning / Probing Path

● Purpose
  ▪ Finding cutter contact point

● Goal position for probe
  ▪ Should penetrate surface
  ▪ \( P_g = P_c + k \cdot D \)
    - \( P_c \) = cutter offset point
    - \( D \) = unit cutter moving direction
    - \( k \) = over shooting size

● Path topology
Path Planning / Cutting Path

- **Purpose**
  - Removing big volume rapidly

- **Path topology**
  - Path file
    - { path layer }
    - { circular path }

- **Computing cutting path**

![Diagram of circular paths on plane, project on top surface, project on bottom surface, blend, and add link and leads.]
Path Planning / Poking Path

- **Purpose**
  - Finish cut
  - Avoid damage to dura mater

- **Goal position for poke**
  - Should penetrate surface

- **Path topology**
Path Planning / Reaming Path

- **Purpose**
  - Reaming out the bottom opening

- **Computing offset point**
  - Projecting points along surface normal direction

- **Tool orientation**
  - Passing apex of cone

- **Path topology**
  - Same with poke path
    - Poke → Move → Cut → Poke → ....
Robot Control for Skull Drilling

- Type of robot motion for skull drilling
  - Move motion
    - To move rapidly
  - Probe motion
    - To detect contact position
  - Cut motion
    - To cut large volume rapidly
  - Poke motion
    - To avoid damage of dura mater
Robot Control / Position Control

- **Cartesian position control**
  - Linear interpolation of start and end points
    - $P(t) = (1-u)\ P_s + u\ P_e$
    - $u = s / |P_e - P_s|$
    - $s = F(t, v, a)$
    - $P_s$ = start position
    - $P_e$ = end position
  - Inverse kinematics
    - $J(t) = \text{Inverse Kinematics of } P(t)$

- **Problem**
  - $P_s$ and $P_e$ are reachable.
  - But
    - Some of $P(t)$ are not reachable.
Robot Control / Checking Force Limits

<table>
<thead>
<tr>
<th>Control Mode</th>
<th>Force Limit (N)</th>
<th>Torque Limit (N mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Force Compliance Mode</td>
<td>40</td>
<td>5000</td>
</tr>
<tr>
<td>Joint Control Mode</td>
<td>4</td>
<td>500</td>
</tr>
<tr>
<td>Cartesian Control Mode</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Move</td>
<td>2</td>
<td>500</td>
</tr>
<tr>
<td>Probe</td>
<td>0.5</td>
<td>500</td>
</tr>
<tr>
<td>Cut</td>
<td>20</td>
<td>2500</td>
</tr>
<tr>
<td>Poke</td>
<td>1 ~ 20</td>
<td>2500</td>
</tr>
</tbody>
</table>
Robot Control / Probe Motion Control

- **Purpose**
  - To stop when the probe contact surfaces

- **Checking magnitude of force while moving**
  - Force limit
    - 0.5N
  - Speed
    - 1 mm/sec

- **Computing a contact point**
  - $Ps = Pc - r \frac{F}{|F|}$
    - $Ps =$ real contact point
    - $Pc =$ tool tip center
    - $F =$ reaction force
    - $r =$ cutter radius

- **Collecting a contact point**
  - Write position to a file
Robot Control / Poke Motion Control

- **Purpose**
  - To stop when the force drop suddenly

- **Control strategy (1)**
  - Checking magnitude of force while moving
    - Parameter = lower limit
  - Complications
    - Noise of force sensor
    - Diversity of cutter, bone density, cutting depth

![Graph showing force over time](image)

\[ Fa \]
\[ Fx \]
\[ ts \]
\[ tx \]
\[ < \text{expectation}> \]
Robot Control / Poke Motion Control

- Control strategy (2)
  - Checking feature of force profile while moving
    - Finding sudden drop
    - Compare the two moving averages
Experiments on Phantom Skull

- Phantom skull with fiducial markers
  - Makers are not original positions with CT data.

- Initial registration
  - # of markers = 10
  - $\text{rms} = 3.7\text{mm}$

- Probing and collecting probe points
  - Maximum feed = $1\ \text{mm/sec}$
  - Acceleration = $2\ \text{mm/sec}$
  - Limit force = $0.5\ \text{N}$
  - # of probe points = 20

- Revised registration
  - Including fiducial markers
    - $\text{rms} = 2.2\text{mm}$
  - Without fiducial markers
    - $\text{rms} = 0.27\text{mm}$
Further Experiments on Cadaver Skull

- Preliminary experiments
  - Finding motion parameters
    - Feed, Acceleration
    - Force profile
    - Force limits

- Main experiments
  - Tool: 3mm diameter
  - Drill: emax
  - Hole: 10mm diameter

- Analysis the results
  - Accuracy of drill hole
  - Damage of dura mater
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