Medical Robots and their Control Paradigms

Peter Kazanzides
Associate Research Professor
Dept. of Computer Science
The Johns Hopkins University
My Background

• 1983-1988 Ph.D. EE (Robotics), Brown University
  – Thesis: Multiprocessor Control of Robotic Manipulators

• 1989-1990 Postdoctoral researcher at IBM
  – Medical robotics (ROBODOC)

• 1990-2002 Co-Founder of Integrated Surgical Systems
  – Director of Robotics and Software
  – Commercial development of ROBODOC® System
  – Sales in Europe (CE Mark) and Asia
  – Clinical trials in U.S. and Japan

• 2002-present Research faculty at JHU
  – Research in use of robotics for neurosurgery, cancer research and therapy, telesurgery, microsurgery, …
Outline

• Overview of ROBODOC System
• Medical robotics at JHU
• What are the control challenges?
• Force control in ROBODOC
• Cooperative Control with Virtual Fixtures
• Constrained optimization formulation
• Conclusions
ROBODOC® System

- Initially developed to assist with Total Hip Replacement (THR) surgery
  - machine femur for cementless prosthesis (femoral stem)
ROBODOC® System

Conventional procedure (mallet and broach)

Computer-assisted planning and execution
ROBODOC Benefits

• Intended benefits:
  – Increased dimensional accuracy
  – Increased placement accuracy
  – More consistent outcome
ROBODOC History

1986-1988 Feasibility study and proof of concept at U.C. Davis and IBM

1988-1990 Development of canine system

May 2, 1990 First canine surgery
ROBODOC History

1990-1995  Human clinical prototype

Nov 1, 1990  Formation of ISS
Nov 7, 1992  First human surgery, Sutter General Hospital
Aug 1994    First European surgery, BGU Frankfurt
## ROBODOC History

### 1995-2002  ROBODOC in Europe and Asia

<table>
<thead>
<tr>
<th>Date</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>March 1996</td>
<td>CE Mark</td>
</tr>
<tr>
<td>April 1996</td>
<td>First 2 installations (Germany)</td>
</tr>
<tr>
<td>Nov 1996</td>
<td>ISS initial public offering (NASDAQ)</td>
</tr>
<tr>
<td>March 1998</td>
<td>First pinless hip surgery</td>
</tr>
<tr>
<td>Feb 2000</td>
<td>First knee replacement surgery</td>
</tr>
</tbody>
</table>
## ROBODOC History

### 2003-2007

<table>
<thead>
<tr>
<th>Date</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oct 2003</td>
<td>Class action lawsuit in Germany</td>
</tr>
<tr>
<td>June 2005</td>
<td>ISS “ceases operations”</td>
</tr>
<tr>
<td>June 2006</td>
<td>German high court ruling against plaintiff</td>
</tr>
<tr>
<td>Sept 2006</td>
<td>ISS resumes operations</td>
</tr>
<tr>
<td>June 2007</td>
<td>ISS sells assets to Novatrix Biomedical</td>
</tr>
</tbody>
</table>

### 2007-present

<table>
<thead>
<tr>
<th>Date</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sept 2007</td>
<td>Curexo Medical formed (Novatrix)</td>
</tr>
<tr>
<td>Sept 2007</td>
<td>Curexo files 510(K) with FDA</td>
</tr>
<tr>
<td>Feb 2008</td>
<td>Company renamed to ROBODOC, a Curexo Technology Company</td>
</tr>
<tr>
<td>Aug 2008</td>
<td>Robodoc receives FDA approval!</td>
</tr>
</tbody>
</table>
ROBODOC Status

- Approximately 50 systems were installed worldwide
  - Europe (Germany, Austria, Switz., France, Spain)
  - Asia (Japan, Korea, India)
  - U.S. (Clinical trial for FDA approval)
- Over 20,000 hip and knee replacement surgeries
- ROBODOC no longer used in Europe
- One Korean hospital uses system regularly – claim 2,500 surgeries/year
- FDA approval in Aug 2008
Medical Robotics at JHU

- Retinal surgery
- Steady hand robot
- Research daVinci
- Needle steering
- Bimanual manipulation
- Snake robot
- Brachytherapy
- Neurosurgery
- SARRP
- Rodent research
- MR-compatible robot
- Spectroscopy
- Smart retractor
- Atlas
- Stereo vision
Control Challenges

• Most medical robots are slow (for safety reasons)
  – Individual joint-level PID control is good enough for position/velocity control

• What about surgery on a beating heart?
HeartLander Robot (CMU)

Miniature mobile robot that adheres to the epicardium and travels to any site for cardiac therapy.

In-vivo testing with beating pig hearts.

Riviere, Patronik, Zenati
Control Challenges

• Robot must work with surgical team
  – Man/machine partnership vs. automation

• Robot must sense and adapt to its environment
  – Force
  – Tissue properties
  – Vision
  – Intraoperative imaging (CT, MR, Ultrasound)
ROBODOC Force Control

- Hand guidance
- Tactile search
- Force-controlled cutting
- Safety threshold
ROBODOC Force Control

Linear Gains

Nonlinear Gains

Force-controlled bone cutting

- Problem: ROBODOC uses fixed cutfiles
  - Conservative cut speeds (assume hard bone)
  - Long cutting times
- Solution: Modify cutter feed rate based on measured force
  - Cutfile specifies minimum and maximum feed rates, as well as maximum force
  - System parameters include tool stiffness
Force-controlled bone cutting

- Technical approach: Use “time warping” in trajectory generator
  - All motions are parameterized by time
  - Plan motion at maximum speed, $s_{\text{max}}$
  - Use time $t_i$ from following equation:

$$t_i = t_{i-1} + \Delta t \cdot \text{arg max} \left( 1 - e^{-R(f_{\text{max}} - f(t))}, \frac{S_{\text{min}}}{S_{\text{max}}} \right)$$

As $f(t) \rightarrow f_{\text{max}}$, warp time to reduce speed to $s_{\text{min}}$

As $f(t) \rightarrow 0$, $t_i \approx t_{i-1} + \Delta T$ (move at $s_{\text{max}}$)

If $f(t) > f_{\text{max}}$, stop robot and cutter
Cooperative Control and Virtual Fixtures

• Generalization of force-controlled guidance and force-controlled cutting

• Steady Hand guidance (JHU)
  – Force-controlled guidance for tremor reduction

• Virtual fixtures
  – Guidance virtual fixtures: constrain motion along a preferred direction
  – Boundary virtual fixtures: prevent motion into a “forbidden zone” (or stay within “safe zone”)
  – Hard vs. soft virtual fixtures
Physical Guidance: Steady Hand Guiding for Microsurgery

Free hand motion

Steady hand motion

R. Taylor & R. Kumar
Copyright © Peter Kazanzides, CISST ERC, 2008
Steady Hand Guiding at the Cellular Level

Kumar, Kapoor, Taylor
Cooperative Control and Virtual Fixtures

• Generalization of force-controlled guidance and force-controlled cutting

• Steady Hand guidance (JHU)
  – Force-controlled guidance for tremor reduction

• Virtual fixtures
  – Guidance virtual fixtures: constrain motion along a preferred direction
  – Boundary virtual fixtures: prevent motion into a “forbidden zone” (or stay within “safe zone”)
  – Hard vs. soft virtual fixtures
Cooperative Control with Virtual Fixtures: Acrobot Robot (Imperial College, London)

• Uses virtual fixtures (Active Constraint Control) to enable surgeon to execute preoperative plan (machine femur and tibia)
Cooperative Control with Virtual Fixtures: Robot for Skull Base Surgery (JHU)

- Uses virtual fixtures to constrain surgeon to remain inside “safe zone” during skull base drilling

Kazanzides, Xia, Baird, Jallo
Virtual Fixture Implementation:
Constrained Optimization

Kapoor & Taylor, 2007
Composition of Virtual Fixtures

Library of primitives
- Stay on a point
- Move along a line
- Maintain a direction
- Prevent plane penetrating
- Rotate around a line

Select one or more

Robot specific constraints

Customized Virtual Fixture

Kapoor & Taylor, 2007
Virtual Fixture Primitives:

1) Stay on a point

Constraint:

$$\|\delta_p + \Delta x_p\| \leq \epsilon_1$$

Polyhedron approximation for sphere of radius $\epsilon_1$:

$$\begin{bmatrix} c_{\alpha_{1i}} & c_{\beta_{1j}} & c_{\alpha_{1i}} s_{\beta_{1j}} & s_{\alpha_{1i}} & 0 & 0 & 0 \end{bmatrix} \cdot (\delta + \Delta x) \leq \epsilon_1,$$

$$c_{\alpha_{1i}} = \cos \frac{i2\pi}{n}; \quad s_{\alpha_{1i}} = \sin \frac{i2\pi}{n}; \quad c_{\beta_{1j}} = \cos \frac{j2\pi}{m}; \quad s_{\beta_{1j}} = \sin \frac{j2\pi}{m}$$

$$i = 0, \ldots, n - 1; \quad j = 0, \ldots, m - 1.$$

Yields constraint: $A \cdot \Delta x \leq b$
Conclusions

• Medical robots have distinct differences from industrial robots:
  – Must work with humans (cooperative)
  – Environment (operating room and patient) is relatively unstructured

• Control challenges are primarily at the higher levels:
  – Man/machine interactions
  – Sensor-based control
Conclusions

• Force control widely used:
  – “Steady hand” guidance
  – Virtual fixtures (mechanical guidance)
  – Tactile search
  – Safety

• High-performance computers enable “real-time” numerical optimization
Acknowledgements

• Faculty
  – Russell Taylor
  – Greg Hager
  – Allison Okamura
  – Gabor Fichtinger
  – Emad Boctor
  – Noah Cowan
  – Cam Riviere
  – Iulian Iordachita

• Numerous Staff and Students

• All my colleagues at Integrated Surgical Systems (ISS)

• Clinicians
  – Paul Flint
  – Michael Choti
  – Daniel Song
  – Ted DeWeese
  – Li-Ming Su
  – David Yuh
  – George Jallo

• Funding