Medical Robotics and Computer-Integrated Therapy Delivery: Coupling Information to Action in 21’st Century Surgery

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Prediction

The impact of computer-integrated surgical systems and technology on medical care in the next 20 years will be as great as the impact of computer-integrated manufacturing systems and technology on industrial production over the past 20 years.

Basic means for fulfilling prediction: systems that integrate information to action

• Provide new capabilities that **transcend human limitations** in surgery
• Increase **consistency and quality** of surgical treatments
• Promote **better outcomes** and more **cost-effective** processes in surgical practice
NSF Engineering Research Center for Computer-Integrated Surgical Systems and Technology

- Multi-institution, multi-disciplinary center
  - Johns Hopkins University + Medical Institutions
  - MIT + Brigham & Women’s Hospital
  - CMU + Shadyside Hospital
- University researchers, clinicians, industry
- Research, Systems, Education, Outreach

Medical robotics and CIS Systems

- Surgical CAD/CAM Systems
- Surgical Assistant Systems
- Concluding remarks
Orthopaedic Surgical CAD/CAM Example: Joint Replacement Surgery

Urologic Surgical CAD/CAM Example: Robotic TURP
Optimized Local Therapy

• Deliver optimized patterns of local treatments (e.g., radiation seeds, injections) with an image-guided robot

• Applications
  – Prostate, brain, spine, liver, bone, kidney ….

• Advantages
  – Accuracy of dose
  – Cost and time of procedure
  – Lower morbidity
  – Avoid complications
  – Enable new treatments

Example: Stereotactic Neurosurgery

Neuromate (ISS)

IGOR (Lavallee, Troccaz, et al)
Example: Radiosurgery

Current ERC focus applications

<table>
<thead>
<tr>
<th>Prostate</th>
<th>Liver</th>
<th>Spine</th>
</tr>
</thead>
<tbody>
<tr>
<td>~210,000 new/year</td>
<td>Mets from colorectal 130,000 new /year</td>
<td>$120 billion cost</td>
</tr>
<tr>
<td>25% men in lifetime</td>
<td>60,000 death /year</td>
<td>70% in lifetime</td>
</tr>
<tr>
<td>~30-40% prostatectomy</td>
<td>~20% radiation seeds</td>
<td>~30-40% extracapsular</td>
</tr>
</tbody>
</table>
One endpoint: 1-stop shopping

Pre-op Screening → Image patient and plan treatment pattern → In-scanner robotically assisted treatment

• Follow up
• Statistics
• Process learning

→ Maintain Treatment Log → Post-op imaging

→ Reimage volume

Key Enablers

• Imaging
  – Image-based modeling & analysis
  – Integration of image sensors with delivery devices for guidance and monitoring
  – Design points set for interventions
Example: integrated MRI imaging and therapy delivery

78 µm resolution!

Combined endoscopic MRI coil & RF ablator
Coaxial transmission line
Surface coil
RF electrodes

Statistical atlas of prostate cancer
Christos Davatzikos & Dinggang Shen

- Labeled images* of 20 subjects for cancer and normal tissue
- Deformably registered images to average prostate (red)
- Computed spatial distribution of cancer (green)
- Computed 5 needle positions to maximize probability of detection
- Use statistical correlation of cancer spatial distributions to optimize pattern

* Images provided by Jianchao Zeng, Georgetown U.
Key Enablers

- Imaging
- Robots & delivery aids
  - Modular designs
  - Compatible with imaging device
  - End effectors

Remote Center of Motion (RCM)

- 2 DOF
- Mechanically constrained motion center
- Maintains entry site

Sketch: Kirby Vosberg, Ferenc Jolesz

Remote Center of Motion (RCM)

R. Taylor, D. Stolanovicl, L. Whitcomb, A. Barnes
Alternate RCM implementations:

Parallel linkages

Goniometer arcs

Photo: D. Stoianovici, JHU Urology Dept
CT-Compatible End-Effector

Phantom Experiment
- Standard prostate phantom
- Demonstrated ~1mm accuracy with robot from single CT image targeting
Clinical example
• Kidney biopsy
• Robot registered to CT from single image using markers on end-effector

Photos: D. Stoianovici, L. Kavoussi, A. Patriciu, S. Solomon (JHU Bayview)
Other contributors: R. Susil, G. Fichtinger, K. Masamune, R. Taylor (JHU WSE)

Clinical example
• Lung biopsy
• Robot registered to CT manually using scanner alignment laser

Credit: D. Stoianovici, L. Kavoussi, A. Patriciu, S. Solomon, JHU Bayview
Ultrasound-Guided Robotically-Assisted Prostate Brachytherapy

Burdette Medical

CISST ERC

Advantages

• Throughput
• Accurate and consistent dose delivery
• Verification
• Data capture
• Improved documentation
Goal: An “Ideal” Brachytherapy System

- Safely performs all routine tasks
  - Imaging
  - Volume definition
  - Dose calculation & visualization
  - Robotically-assisted seed placement
  - Data logging
- Leaves clinician free to focus on therapy

In-MRI Biopsy (FZK)

Photos: Harald Fischer
FZ Karlsruhe
Key Enablers

- Imaging
- Robots & delivery aids
- Integrated systems

Integration Example: Open-MR Brachytherapy System (BWH/MEL)

- MR-compatible mechanical manipulator
- Pneumatic and ultrasound motors
- 5 DOF holder

Credit: K. Chinzei & N. Hata
Open MRI robot system overview

CT-guided robot system overview
**Ultrasound-guided robot system**

- Robot control PC
- Security monitoring host
- Ultrasound Robot
- Intraoperative ultrasound
- High-Bandwidth Network
- Visualization Workstation
- Planning System

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**Surgical CAD/CAM Examples**

- **Robot-assisted execution**
  - Joint replacement
  - Percutaneous therapies

- **Navigation-assisted execution**
  - Navigation systems for brain, spine, ENT
  - Evolution: Information-enhanced minimally-invasive surgery
Computer-assisted planning

Patient-specific Model

Preoperative

Update Model

Update Plan

Computer-Assisted Execution

Intraoperative

Postoperative

Atlas

Patient

Computer-Assisted Assessment

Cutting, Bookstein, Taylor, et al.
Navigation Systems

Example: Pedicle Screw Placement

Photos: Orthosoft, Inc.
Example: Cup Placement in THR

Example: “Virtual Fluoroscopy”

- Computer tracks patient, instruments, and x-ray c-arm
- Computer overlays real-time graphics onto x-ray images
- Advantages
  - Reduced x-ray exposure
  - Easy to learn & use
- Limitations
  - 2D projections
  - Relies on accurate tracking

Source: Sofamor Danek, Inc.
Example: Advanced Image Overlay

Photo: CMU and Shadyside Hospital
Medical robotics and CIS Systems

- Surgical CAD/CAM Systems
- Surgical Assistant Systems
- Some concluding remarks

Surgical Assistant Examples

- Navigation-assisted execution
  - May be viewed as “information assistants” for surgery
- Robotic systems
  - Endoscopic surgery
  - Microsurgery
- Evolution: a grand fusion
Skilled Tasks

• Situation assessment
• Task strategy & decisions
• Sensory-motor coordination

Skilled Task Augmentation

• Situation assessment
• Task strategy & decisions
• Sensory-motor coordination

• Sensor processing
• Model interpretation
• Display
• Online references & decision support
• Manipulation enhancement
• Cooperative control and “macros”
Example: Robotic endoscope Holders

- Robot holds endoscope
- Surgeon controls view through various interfaces
  - Joystick or foot pedal
  - Voice recognition
  - Head or eye tracking
- Main current justifications
  - Labor cost saving
  - Somewhat steadier view

Photo: Computer Motion, Inc
Example: Robotic retraction assistant
Ultrasound Manipulation Robots

Salcludean ultrasound system

Hippocrates Robot
E. Degoulange, et al

High Dexterity End-Effector

Credit: Randy Goldberg
High Dexterity End-Effector for Ultrasound

Credit: Randy Goldberg
Volume Scan Demonstration

Credit: Randy Goldberg

Volume Scan Demonstration - Rotation

Credit: Randy Goldberg
Volume Scan Demonstration - Fan

Volume Scan Demonstration - Translation

Credit: Randy Goldberg
Applications/Future Development

- Image volume reconstruction
- Real time tracking & registration
- Ultrasonography skill enhancement
- “Third hand” for ultrasound-guided interventions

Photo: Randy Goldberg

Robotic Assistants for Microsurgery

By Mike Peters

Eventually, the lab was forced to move
Microsurgical Assistant

- Develop human augmentation systems to assist surgeons in delicate microsurgical procedures
- Applications
  - Eye, ENT, Neurosurgery, Vascular
- Advantages
  - Tremor, precision, force feedback
  - Information integration
  - New procedures (e.g., injections into retinal vessels)

Example Procedure

*Retinal Vein Cannulation*: the insertion of a needle into the lumen (interior) of a retinal vein or artery in order to introduce therapeutic drugs.

[Diagram of retina with detailed microstructure and cannulation process]
Stapedotomy drilling

• Have established surgical simulation station for evaluating stapedotomies
• Clinical problem is making very small hole in stapes (bone in middle ear) without damaging inner ear
• Quantitative outcome measures
  – Compare robot-assisted versus unaided procedure

Cooperative force guiding of surgical robots

Photo: JHU

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Steady Hand Guiding for Microsurgery

\[ K_v \]

Handle force

R. Taylor, R. Kumar, P. Jensen, L. Whitcomb, J. Roy
Steady Hand Force Scaling Concept

Handle force \( K_{\text{handle}} \) \( K_v \)
Tip force \( K_{\text{tip}} \)

High-resolution visualization sensors

Operating Microscope

Next-generation end effector

GRIN Lens Endoscope

Movie
Robot as stable platform for intraoperative sensing

Free hand motion

Steady-hand motion

positions

images

R. Kumar, P. Jensen, G. Hager
Movies: CISST ERC, MADLAB, JHU

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Evolution: Integrate imaging and robots

- In-scanner visualization and guidance
- Steady-hand robots for ultrasound & instrument manipulation
- Applications include biopsies, ablations, MIS

Telerobotic Surgical Augmentation

- Surgeon manipulates “master” robot
- “Slave” robot mimics motions
- Typically systems have:
  - Force & position scaling
  - Remote visualization via video
- Can be expensive but provide improved capability for minimally invasive procedures
Evolution: Augmented Teleoperation

- Situation assessment
- Task strategy & decisions
- Sensory-motor coordination

Augmentation System
- Sensor processing
- Model interpretation
- Display
- Online references & decision support
- Manipulation enhancement
- Cooperative control and “macros”

R. Taylor
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Example: Robotic Knot Tying

Medical robotics and CIS Systems

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Medical robotics and CIS Systems

- Robots are simply information-driven surgical tools
- Their real potential will come from their use within the context of computer-integrated surgical systems.
- There is much research to be done.

Research and technology barriers

Modeling & analysis
- Segmentation
- Registration
- Atlases
- Optimization
- Visualization
- Task characterization
- etc.

Interface Technology
- Sensing
- Robotics
- Human-machine interfaces

Systems
- Safety & verifiability
- Usability & maintainability
- Performance and validation
How can we get there?

Strong and committed teams
- Surgeons
- Engineers
- Industry

Focus on systems that address important needs

Rapid iteration with measurable goals

Have fun!

The real bottom line: patient care

- Provide new capabilities that **transcend human limitations** in surgery
- Increase **consistency and quality** of surgical treatments
- Promote **better outcomes** and more **cost-effective** processes in surgical practice