Computer-Integrated Surgery

Russell H. Taylor
Dept. of Computer Science/Radiology/Mechanical Engineering
Director, Center for Computer-Integrated Surgical Systems and Technology
The Johns Hopkins University
3400 N. Charles Street; Baltimore, Md. 21218
rht@cs.jhu.edu
Thanks to many people …

- J. Anderson
- W. Bargar
- A. Bzostek
- B. Eldridge
- G. Fichtinger
- J. Funda
- F. Frassica
- R. Goldberg
- S. Gomory
- G. Hager
- L. Joskowicz
- Y. Kim
- R. Kumar
- D. Shen
- C. Riviere
- D. Yousem
- A. Kalvin
- C. Cutting
- A. Morris
- J. Lazarus
- D. Long
- K. Masamune
- K. Murphy
- D. Yousem
- B. Jaramaz
- A. DiGioia
- A. Lahmer
- M. Borner
- A. Bauer
- A. Barnes
- P. Jensen
- J. Yao
- B. Mittelstadt
- M. Li
- D. Sheng
- D. Rothbaum
- A. Gueziec
- M. Talamini
- K. Chinzei
- N. Hata
- R. Kikinis
- D. Stoianovici
- A. Patriciu
- L. Whitcomb
- A. Okamura
- C. Davatzikos
- E. Atalar
- E. Zerhouni
- L. Kavoussi
- P. Kazanzides
- H. Paul
- J. Wenz
- E. DeJuan
- J. Roy

… and many more
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.
Computers and networks

- Image & sensor processing, anatomical modeling, surgical planning and control, ...

Interface technology

- Imagers and other sensors
- Robotic devices
- Human-machine interfaces

Images & other sensor data

Command & control

Decision support & commands

Patient data bases

Anatomic atlases and surgical task models

Patient

Surgeon
Computer-assisted planning

Patient-specific Model

Update Model

Update Plan

Computer-Assisted Execution

Preoperative

Intraoperative

Postoperative

Patient

Atlas

Computer-Assisted Assessment
Preoperative

Computer-assisted planning

Patient-specific Model

Intraoperative

Update Model

Update Plan

Computer-Assisted Execution

Surgical “CAD”

Patient

Surgical “CAM”

Surgical “TQM”

Postoperative
Process Vision: “One stop shopping” therapy

- Fully integrated and optimized planning, execution, assessment, and follow-up of minimally invasive interventional procedures
- ... for a broad spectrum of clinical conditions
- ... anywhere in the body
- ... with convenience comparable to current outpatient diagnostic procedures.
System Vision: “Plug and Play” Surgery

- A modular family of subsystems, including
  - imaging devices and methods
  - modeling & analysis algorithms
  - robotic devices
  - visualization & human-machine interfaces
  - systems development tools …

- which can be **quickly integrated** with novel therapeutic end effectors to produce …

- complete and effective surgical CAD/CAM systems with **predictable and certifiable performance** …

- for **multiple** organ systems, therapeutic approaches, and imaging modalities.
Computer-assisted planning

Patient-specific Model

Surgical Assistants

Preoperative

Postoperative

Atlas

Computer-Assisted Assessment

Copyright © CISST ERC, 2002
Vision: “Information-intensive” surgery

- Surgical systems interfacing to an information-rich surgical environment
- ... and capable of using this information to maintain patient-specific models
- ... registered in real time to the physical reality of the operating room
- ... with the ability to use these models to assist surgeons in carrying out complex surgical procedures
- ... through robotic assists and information display devices.
Vision: “super-human” surgical teams

• Surgical systems capable of modeling and following the progress of a surgical procedure,
• … and able to use robotic devices and sensors extending human performance
• … cooperatively with the surgeon
• … in order to improve the quality of surgical procedures and to enable interventions that would be otherwise impossible.
• Multi-institution, multi-disciplinary center
  – Johns Hopkins University + Medical Institutions
  – MIT + Brigham & Women’s Hospital
  – CMU + West Penn. Allegheny Health System
  – Others: Morgan State, Georgetown, Harvard
• University researchers, clinicians, industry
• Research, Systems, Education, Outreach
Technical barriers: Knowledge and Systems

Credit: K. Chinzei & N. Hata
Non-Technical Barriers: The Three Cultures

The three cultures

Academic Researchers

Clinicians

Industry
Non-Technical Barriers: Education

Undergrad & postgrad
Continuing professional

K-12
The CISST ERC addresses these barriers

• Multidisciplinary systems – oriented research leveraging our environment
• Engineering faculty + clinicians + industry
• Education integrated into all aspects
The CISST ERC addresses these barriers

- Multidisciplinary systems – oriented research leveraging our environment
- Engineering faculty + clinicians + industry
- Education integrated into all aspects
The CISST ERC addresses these barriers

- Multidisciplinary systems – oriented research leveraging our environment
- Engineering faculty + clinicians + industry
- Education integrated into all aspects
Research-based Education

Integrate education into all aspects of research and industry programs

- **Engineered systems & applications**
- **Enabling core technology**
- **Fundamental knowledge**

Independent study & internships

Project courses

“Regular” courses

Copyright © CISST ERC, 2002
Education Highlight:
High School Research Project

• Intelligent hand tool for computer-assisted knee cartilage surgery
• High school student
  – Al Brzechko (Baltimore Polytechnic HS)
• Mentors
  – R. Goldberg (MS student)
  – P. Evans, MD (surgeon)
  – R. Taylor, Ph.D (faculty)
• Status
  – Prototype device built
  – Paper accepted at MICCAI 2001
  – Surgeon pursuing commercial partner for next phase
Surgical Robot Lego Competition for High School Students
Computer-Integrated Surgery

• Surgical CAD/CAM Systems

• Surgical Assistant Systems

• Some concluding remarks
Robotic Joint Replacement Surgery
Statistical Atlas

"Virtual CT"

Deformable 2D-3D

Updated Plans

Registered Model

Visualization & Guidance

Rigid 2D-3D

X-rays

X-rays

X-rays

R. Taylor & J. Yao

Copyright © CISST ERC, 2002
3D models from incomplete data

Prior Information

Registration

Reconstruction

# Projections

100 degrees
2D/3D Deformable Registration

Jianhua Yao
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
## Current ERC percutaneous focus applications

<table>
<thead>
<tr>
<th></th>
<th>Prostate</th>
<th>Liver</th>
<th>Spine</th>
<th>Bone Cancer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>~210,000 new/year</td>
<td>Mets from colorectal</td>
<td>$120 billion cost</td>
<td>600,000 metastatic cases/year</td>
</tr>
<tr>
<td></td>
<td>25% men in lifetime</td>
<td>130,000 new /year</td>
<td>70% in lifetime</td>
<td></td>
</tr>
<tr>
<td></td>
<td>~30-40% prostatectomy</td>
<td>60,000 death /year</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>~20% radiation seeds</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>~30-40% extracapsular</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
One endpoint: 1-stop shopping

Pre-op Screening

- Follow up
- Statistics
- Process learning

Image patient and plan treatment pattern

In-scanner robotically assisted treatment

Reimage volume

Maintain Treatment Log

Post-op imaging

One endpoint: 1-stop shopping
Clinical example: X-ray guidance

- Percutaneous access to kidney
- Radiolucent needle driver
- Robot aligns needle under x-ray fluoroscopy guidance
- Has been done both locally and remotely

Photos: D. Stoianovici, L. Kavoussi
X-ray guided breast biopsy
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)
Early ultrasound guided example:
Robotic TURP
Ultrasound-guided prostate brachytherapy

• Combined Phase I/II SBIR with Burdette Medical Systems
• Goal is “one stop shopping” system for ultrasound-guided prostate brachytherapy
Integration Example: Open-MR Brachytherapy System (BWH/MEL)

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

Credit: K. Chinzei & N. Hata
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.
In-MRI prostate biopsy

Why use MRI?

• Good tissue contrast.
• Excellent sensitivity for detecting tissue abnormalities.
• May allow for ‘targeted’ biopsy and improved diagnostic sensitivity
In-MRI imaging

R. Susil, G. Fichtinger, E. Atalar

Copyright © CISST ERC, 2002
Interventional Device

Mimics design and functionality of US transrectal biopsy device, but allows for control while patient is in MRI scanner

R. Susil, G. Fichtinger, E. Atalar

Copyright © CISST ERC, 2002
Example: integrated MRI imaging and therapy delivery

78 µm resolution!

Canine urethra

Beagle prostate

Combined endoscopic MRI coil & RF ablator

Coaxial transmission line

Surface coil

Scanner

E. Atalar, JHU
Cutting, Bookstein, Taylor, et al.
CT Overlay

Masamune, Fichtinger, Taylor, et al.
Computer-Integrated Surgery

• Surgical CAD/CAM Systems

• Surgical Assistant Systems

• Some concluding remarks
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
Our current focus: mostly Eye & ENT

Eye:
- Retinal vein cannulation
- Retinal translocation
- ...

ENT:
- Stapes prosthesis
- Cochlear implant
- ...

Microvascular Neurosurgery

Retina with occluded retinal vein

2 mm
Steady Hand Guiding for Microsurgery

Free hand motion

Steady hand motion

Handle force

$K_v$
Successful cannulation of an approx. 100 micron blood vessel (Kumar, 2001)
Ultrasound Manipulation Robots

Salcludean ultrasound system

Hippocrate Robot
E.Degoulange, et al
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

Photo: Intuitive Surgical
Evolution: “Smart” telesurgery

- 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”

atlases
libraries

R. Taylor
Research & Technology Barriers

Performance assessment
- Metrics & measurements
- Human baseline data
- System evaluation

Task & task element characterization

System infrastructure, integration, and end user experience

Human-machine interfaces
- Displays & visualization
- Haptic input/output
- Voice

Robotics & cooperative control

Sensor processing, modeling, and anatomical atlases

Augmentation System

Robotics & cooperative control

Sensor processing, modeling, and anatomical atlases

Human-machine interfaces
- Displays & visualization
- Haptic input/output
- Voice
Computer-Integrated Surgery

- Surgical CAD/CAM Systems
- Surgical Assistant Systems
- Concluding remarks
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