Acknowledgments

- **This is the work of many people**

- Some of the work reported in this presentation was supported by fellowship grants from Intuitive Surgical and Philips Research North America to Johns Hopkins graduate students and by equipment loans from Intuitive Surgical, Think Surgical, Philips, Kuka, and Carl Zeiss Meditec.

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- Much of this work has been funded by Government research grants, including NSF grants EEC9731478 and IIS0099770 and NIH grants R01-EB016703, R01-EB007969, R01-CA127144, R42-R019159, and R21-EB0045457; by Industry Research Contracts, including from Think Surgical and Galen Robotics; by gifts to Johns Hopkins University from John C. Malone, Richard Swirnow and Paul Maritz; and by Johns Hopkins University internal funds.
A short personal background: Russ Taylor

• 1970: BES from Johns Hopkins
• 1976: PhD in CS at Stanford
• 1976-1988: Research/management in robotics and automation technology at IBM
• 1988 - 1996: Medical robotics & computer-assisted surgery at IBM
  – Robodoc
  – Surgical navigation
  – Robotic assisted MIS and percutaneous interventions (with JHU)
• 1995: Moved to JHU
  – CS with joint appts in ME, Radiology, Surgery (2005)
  – X-ray guided MIS & orthopaedics
  – “Steady Hand” microsurgery
  – Radiation therapy
  – Modeling & imaging
  – Etc.
• 1997 - now: NSF ERC; LCSR

Motivating Insight

A partnership between human clinicians and computer-based technology will fundamentally change the way surgery and interventional medicine is performed in the 21st Century, in much the same way that computer-based technology changed manufacturing in the 20th Century.
Goal: Human-machine partnership to fundamentally improve interventional medicine

Physicians

Technology

Information

Over 25 years ago: Robotic Joint Replacement Surgery

Taylor, Kazanzides, Paul, Mittelstadt, et al.
Emerging: Information-Augmented Robotic Surgery


Emerging: Augmented Reality in the OR


* Joint first authors
Computer-Integrated Interventional Medicine

Model → Diagnose → Plan → Intervention

Patient-Specific Data
- Images, lab data, genomics
- Clinical history
- Models & plans
- Etc.

Assess

General/Multi-Patient Data
- Statistical anatomic atlases
- Disease/pathology data
- Genomic data bases
- Planning rules
- Outcomes statistics
- Etc.
Computer-Integrated Interventional Medicine

General/Multi-Patient Data
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Model → Diagnose → Plan → Assess

Intervention

This Paradigm has not changed since Imhotep’s day

But medical robots and computer-integrated interventional systems will make it much more effective

27th Century SCE

21st Century CE
Multidisciplinary Integration is Crucial

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

Image-based modeling & analysis

General/Multi-Patient Data
- Statistical anatomic atlases
- Disease/pathology data
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- Planning rules
- Outcomes statistics
- Etc.

Patient-Specific Data
- Images, lab data, genomics
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- Models & plans
- Etc.

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Engineering Research Center for Computer Integrated Surgical Systems and Technology
Patient-Specific Models for Interventions

- Computationally efficient \textbf{representation of patient} enabling computer to assist in planning, guidance, control, and assessment of interventional procedures
- Generally focus on \textbf{anatomy}, but may sometimes include biology or other annotations
- Predominately derived from medical images and image analysis
- Increasingly reference statistical \textit{“atlases”} describing patient populations


Combining prior knowledge with online images

- Prior images & models (mostly 3D)
- New Images (2D, 3D)
- Prior statistical information (atlas)

\textbf{Computational process}
- Segmentation
- Registration
- Hybrid reconstruction

\textbf{Applications}
- Intervention planning
- Intervention guidance & visualization
- Biomechanical analysis

Video: JH Yao, 2002
Deformable 2D/3D Registration to Statistical Atlas

Prior statistical information (atlas) → Computational process → Patient-specific model

Applications
- Orthopaedic surgery planning
- Biomechanical analysis
- Hybrid reconstruction

Examples: R. Taylor, J. Yao, O. Sadowsky, G. Chintalapani, O. Ahmad, …

Model Completion, Given Partial CT + X-rays


Prior statistical information (atlas) → Computational process → Patient-specific model

Partial CT Scan → Atlas Extrapolation

2 X-ray Images → 2D/3D Registration

Hip Osteotomy
- Biomechanical analysis
- Intraoperative registration
Procedure Planning

- Highly procedure-specific
- Occurs at many time scales
  - Preoperative
  - Intraoperative
  - Preop. + intraop. update
- Typically based on images or segmented models
- May involve:
  - Optimization
  - Simulations
  - Visualization & HCI
Procedure Planning

• Typical outputs
  – Target positions (seeds, biopsies, ablation sites, etc.)
  – Tool paths
  – Desired geometric relationships
  – Key-frame visualizations
  – Images, models & control parameters

• Emerging themes
  – Atlas-based planning
  – Statistical process control & integration of outcomes into plans
  – Dynamic, interactive replanning

Procedure Execution

General/Multi-Patient Data
  • Statistical anatomic atlases
  • Disease/pathology data
  • Genomic data bases
  • Planning rules
  • Outcomes statistics
  • Etc.

Model → Diagnose → Plan

Patient-Specific Data
  • Images, lab data, genomics
  • Clinical history
  • Models & plans
  • Etc.

Assess ➔ Intervention

Photos: Mehran Armand
Procedure Execution

- Highly procedure-specific
- Don’t always have a robot
  - Surgical Navigation
  - Image Overlay
- But robots can transcend human limitations
  - to make procedures less invasive,
  - more precise,
  - more consistent,
  - and safer

Masamune, Fischer, Deguet, Coune, Taylor, Sauer, lortie, Masamune, Eronich, Fichtinger, …

Solomon et al.
Okamura et al.
Procedure Execution

- Highly procedure-specific
- Don’t always have a robot
  - Surgical Navigation
  - Image Overlay
- **But robots can transcend human limitations**
  - to make procedures less invasive,
  - more precise,
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Procedure Execution

- Highly procedure-specific
- Don’t always have a robot
  - Surgical Navigation
  - Image Overlay
- **But robots can transcend human limitations**
  - to make procedures less invasive,
  - more precise,
  - **more consistent,**
  - and safer
Procedure Execution

- Intraoperative systems typically combine multiple elements
  - Imaging
  - Information fusion
  - Robotics
  - Visualization and HMI

- Issues
  - Design
  - Imaging compatibility
  - OR compatibility
  - Safety & sterility
  - Intelligent control
  - Human-machine cooperation

Image-guided needle placement

Masamune, Fichtinger, Iordachita, ...

Okamura, Webster, ...

Krieger, Fichtinger, Whitcomb, ...

Fichtinger, Kazanzides, Burdette, Song, ...

Iordachita, Fischer, Hata, ...

Taylor, Masamune, Susil, Patriciu, Stoianovici, ...
Information-enhanced robotic surgery

Augmented reality displays imaging
Safety barriers
Shared control
“Virtual fixtures”

Example: Challenges in Precise Minimally Invasive Head-and Neck Surgery

- Long (25cm) instruments
  - Amplify hand tremor
  - Reduce precision
- Tight spaces near sensitive anatomy
- Limited working area
The Robotic ENT Microsurgery System (REMS)

User interface:
- Hands-on control, surgeon "in the game"
- Foot pedal-controlled gain

Technical specs:
- Up to 0.025 mm precision on-demand
- 6 degrees of freedom
- 125x125x125mm work volume
- Calibrated accuracy ~50-150μm

Control modes:
- Free hand
- Remote center of motion
- Virtual fixture avoidance
- Teleoperation

K. Olds, Robotic Assistant Systems for Otolaryngology-Head and Neck Surgery, PhD thesis in Biomedical Engineering, Johns Hopkins University, Baltimore, March 2015.

Cadaver Study: Sinus Surgery with Virtual Fixtures

Robot-assisted Sinus Surgery Cadaver Demonstration

K. Olds, M. Balicki, M. Ishii, R. Taylor
The Galen Platform

**Technology:**
- Custom 5-DOF architecture
- “Steady Hand” cooperative control
- Hand tremor cancellation
- Virtual fixtures

**Ease of Use:**
- Same footprint as a person
- Accommodates standard instruments
- Minimal change to existing surgical workflow

**Broad Applications:**
- ENT, spine, brain, trauma, ….  

**Disclosure:** Prof. Taylor is a paid consultant to and has equity in Galen Robotics and also may receive income from patent royalties from Galen.

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Snake-like robot for minimally invasive surgery

**Goals**
- Develop scalable robotic devices for high dexterity manipulation in confined spaces
- Demonstrate in system for surgery in throat and upper airway

**Approach**
- “Snake-like” end effectors with flexible backbones and parallel actuation
- Integrate into 2-handed teleoperator system with optimization controller

**Status**
- Licensed to industry partner
- Significant research at Vanderbilt

**Funding**
- NIH R21, CISST ERC, JHU, Columbia
- NIH proposals pending

New technology finally allows true evaluation of the potential of single port access surgery. Systems raise new questions about control and telemanipulation infrastructure/cooperative control.

Single Port Access Surgery

Nabil Simaan (Vanderbilt, Columbia), with P. Allen (Columbia), D. Fowler (Columbia)

Single Port Access Robotic Surgery

Titan Medical Sport
https://www.youtube.com/watch?v=jlvjcKA6xQ

Intuitive Surgical Sp
https://www.youtube.com/watch?v=-jm63JdTrp4
Minimally-Invasive Osteolysis Curettage

Planning Workstation
- Patient modeling
- FEM analysis
- Plan optimization
- FEM updates
- Plan revisions

Intraoperative Workstation
- 2D-3D registration
- Optical tracking
- Workflow control
- Model updates
- Human Interface
- 3D Visualization
- Robot Control

Preoperative CT Data

C-Arm
Optical Tracker

Positioning Robot
Haptic Device
Fiducial Attachment

Planes & images
Treatment updates

M. Armand, R. Taylor, M. Kutzer, R. Murphy, S. Segretti, Y. Otake, et al.

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Engineering Research Center for Computer Integrated Surgical Systems and Technology
**Curved Drilling of the Femoral Head**

Alambeigi, *et al.*

- Osteonecrosis of the femoral head
  - More than 20,000 patients per year
  - To reduce the pressure in the femoral head, core decompression was developed more than three decades ago.

- Steerable “snake” with flexible drill provides better

---

**Foreign Bodies in the Heart**

**Causes**  
Thrombi, Shrapnel 
Iatrogenic

**Symptoms**  
Cardiac Tamponade  
Hemorrhage  
Arrhythmia  
Infection  
Shock  
Embolism  
Valve Dysfunction

**Conventional Treatment**  
Median Sternotomy  
Cardiopulmonary Bypass


*Actis Dato, 2003*  
*LeMaire, 1999*
Beating Heart MIS with 3D US Guidance
Paul Thienphrapa, Aleksandra Popovic, Russell Taylor

Workstation Computer  +  Philips 3D Ultrasound

Combined RCM Robot and Dextereous Manipulator

US Beacon (on tip)

Foreign Body

3D TEE Probe

Cone Beam CT (optional)

Philips 3D Ultrasound

Retrieval Experiment Results

Thienphrapa et al. 2013
Vitreoretinal Microsurgery

Microsurgery Assistant Workstation

- 3D Display with Overlays
- Stereo video Microscope
- EyeRobot2
- Audio Output
- OCT Display
- Force and OCT sensing tools
- FBG Interrogator
In-Vivo Experiments

- Overall System Performance
- System Ergonomics
- Collect Data
  - Robot / Force / OCT
  - Video / Audio

Patient-specific assessment and feedback
Elastography monitoring of ablations

Ex vivo

B-mode image | Displacement image | Strain image | Gross pathology image

ultrasound | elasticity | post-operation CT

patient 1

patient 2

Credit: Boctor, Rivaz, Choti, Højgaard, et al.

Statistical Analysis and Decision Support

General/Multi-Patient Data
- Statistical anatomic atlases
- Disease/pathology data
- Genomic databases
- Planning rules
- Outcomes statistics
- Etc.

Model
Diagnose
Plan
Intervention

Patient-Specific Data
- Images, lab data, genomics
- Clinical history
- Models & plans
- Etc.

Assess

Credit: Boctor, Rivaz, Choti, Højgaard, et al.
Information-Integrated Process Learning

- **Key idea**
  - Medical robots and CAI systems inherently generate data and promote consistency
  - Eventually, outcomes are known
  - Combine this information over many patients to improve treatment plans / processes

- **Issues / Themes**
  - Very large data bases combining heterogeneous data
  - Statistical modeling of patients, procedures, and outcomes
  - Online tracking of procedures

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Outer/Population Loop

*Current Trial Practice*
- Data Collection
- Treatment Protocol
- Literature Search
- Data Analysis
- Journal Publication

*Hypothetical Future Practice*
- Data Collection
- Treatment Protocol
- Data Analysis
- Journal Publications
- Publication of Data to DB

- Increased potential for data reuse
- Publications with live data!

*Figure: Todd McNutt*
**Statistical process control for radiation therapy**

**Overall Goal:** Use a database of previously treated patients to improve radiation therapy planning for new patients

**Team:**
- **CS:** R. Taylor, M. Kazhdan, P. Simari, A. King
- **BME:** R. Jacques
- **Rad. Oncology:** T. McNutt, J. Wong, B. Wu, G. Sanguinetti (MD)
- **Support:** Paul Maritz, Philips, JHU internal funds

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**Input to planning process**

1. **Patient Database**
2. **New patient OVH**
3. **Identify patients with similar OVHs**
4. **Best DVH for similar patients**

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**Quality control check**

1. **Current planning process**
2. **Optimize treatment parameters**
3. **Simulate treatment & visualize results**
4. **Specify Optimization Goals & Constraints**

---

**New patient PTV and critical structures**
Applications Of Surgical Motion Models

**Underlying hypothesis:** Learned motion models of experts can be used for teaching, training, and automation of surgical actions.

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The Language of Surgery

Hager, Khudanpur, Vidal + Chen, Lee, Ishii

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G. Hager, et al.
Example: Automatic Detection and Segmentation of Robot-Assisted Surgical Motions

• Goals:
  – Automatic recognition of different surgical motions
  – Comparison of skill level differences between surgeons

• Method
  – Extract features from position and velocity traces
  – Linear discriminant analysis with probabilistic Bayesian classifier


Unstructured surgeries: Discovering “teachable” tactics

Septoplasty: “index” surgery

Feedback: Stroke Curvature Consistency: Draw similar-shape curves (instead of straight lines) sequentially
Stroke Duration Consistency: Spend the same amount of time drawing the curves
Coverage Rate: Practice strong enough brushing motions to elevate mucosa

OR Workflow Observation and Analysis
N. Navab et al.

Information-Intensive Interventional Suite

Data Logging & Summary
Logistics & scheduling
PACS, other patient data bases

Imaging systems
- Xray, US,
- CT, MRI, etc.

Assistant Workstation

Anesthesia, vital signs,
logistics, back table, etc.

OR video

Robots

Surgeon Interfaces
The computer-integrated operating room

Patient Loop

- "smart tool" sensors
- Intraoperative information support
- Preoperative images & other data
- Manipulation assistance

Process Loop

- Complete record of intervention
- Outcome data
- Postoperative analysis & process improvement

Robotic devices

Intraoperative analysis

- Video
- Manipulation assistance

Preoperative images & other data

Complete record of intervention

Outcome data

Postoperative analysis & process improvement

Complete record of intervention

Outcome data

Intraoperative analysis

Complete record of intervention

Outcome data

Postoperative analysis & process improvement

Complete record of intervention

Outcome data

Postoperative analysis & process improvement

Complete record of intervention

Outcome data
The computer-integrated operating room

- Manipulation assistance
- Intraoperative information support
- Intraoperative analysis
- Preoperative images & other data
- Postoperative analysis & process improvement
- Complete record of intervention
- Outcome data
- Postoperative analysis & process improvement
- Complete record of intervention
- Outcome data

The computer-integrated operating room

- Manipulation assistance
- Intraoperative information support
- Intraoperative analysis
- Preoperative images & other data
- Postoperative analysis & process improvement
- Complete record of intervention
- Outcome data
Use Case: da Vinci Research Kit

- Mechanical components from da Vinci “classic” systems
- Donated by Intuitive Surgical to selected university labs
- Consortium to provide “open source” engineering and support
  - Software – JHU (CISST/SAW)
  - Controller electronics – JHU
  - Interface electronics – ISI
  - Controller power/packaging – WPI
- Controllers and software also adapted for use with complete recycled da Vinci “classic” systems
- [http://research.intusurg.com/dvrkwiki/](http://research.intusurg.com/dvrkwiki/)
General working model

Use clinical applications to provide focus & key problems
• Emphasis on surgery and interventional procedures
• Directly involve clinicians in all stages of research
• Emphasize integration into complete systems
• Point toward clinical deployment

Some current areas include
• Skull base and head-and-neck
• Spine and orthopaedic surgery
• Thoracic surgery
• Abdominal and solid organ procedures (kidney, liver, prostate)
• Vascular & endoluminal
• Microsurgery

Funding models
• NIH, other Government grants
• Collaboration with NIH intramural programs
• Industry partnerships (use master research agreements to facilitate)

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
Discussion