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.

- Some of the work reported in this talk incorporates intellectual property that is owned by Johns Hopkins University and that has been or may be licensed to outside entities, including Intuitive Surgical, Varian Medical Systems, Philips Nuclear Medicine, Virtuoso Technologies, Galen Robotics and other corporate entities. Prof. Taylor and the University are entitled to royalty distributions related to this technology, and Dr. Taylor has received or may receive some portion of these royalties. Also, Dr. Taylor is a paid consultant to and owns equity in Galen Robotics, Inc. These arrangements have been reviewed and approved by JHU in accordance with its conflict of interest policy.

- Much of this work has been funded by Government research grants, including NSF grants EEC9731478 and IIS0099770 and NIH grants R01-EBO16703, R01-EB007969, R01-CA127144, R42-RK019159, 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
  - Robotically 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

Over 25 years ago: Robotic Joint Replacement Surgery
Emerging: Information-Augmented Robotic Surgery

Emerging: Augmented Reality in the OR


* Joint first authors
Computer-Integrated Interventional Medicine

Model  Diagnose  Plan  Asses  Intervention

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

Computer-Integrated Interventional Medicine

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

Model  Diagnose  Plan  Assess  Intervention

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

Copyright © 2018 R. H. Taylor
This Paradigm has not changed since Imhotep’s day

But medical robots and computer-integrated interventional systems will make it much more effective
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
- Genomic data bases
- Planning rules
- Outcomes statistics
- Etc.

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

Model
Diagnose
Plan
Assess

Intervention
Patient-Specific Models for Interventions

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


Combining prior knowledge with online images

- Prior statistical information (atlas)
- Prior images & models (mostly 3D)
- New Images (2D, 3D)
- Computational process
  - Segmentation
  - Registration
  - Hybrid reconstruction
- Patient-specific model
- 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

Atlas Extrapolation

Patient-specific model

Hip Osteotomy
- Biomechanical analysis
- Intraoperative registration

Partial CT Scan

2 X-ray Images

2D/3D 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.

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

- **Model**
- **Diagnose**
- **Plan**
- **Assess**
- **Intervention**
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, Daquet, Caouette, Taylor, Sauer, Iorchidata, Masamune, Chronich, Fichtinger, ...

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

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,
  – more consistent,
  – and safer
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, ...
Information-enhanced robotic surgery

- augmented reality displays imaging
- safety barriers
- shared control
- “virtual fixtures”
- SAW

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

Cadaver Study: Sinus Surgery with Virtual Fixtures

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

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

Single Port Access Surgery

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 Robotic Surgery

Titan Medical Sport
https://www.youtube.com/watch?v=jlvjcKAl6xQ

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
- Work flow control
- Model updates
- Human Interface
- 3D Visualization
- Robot Control

Preoperative CT Data

C-Arm
Optical Tracker

Plots & Images
Treatment updates
Planning Workstation

Positioning Robot
Haptic Device

Fiducial Attachment

M. Armand, R. Taylor, M. Kutzer, R. Murphy, S. Segretti, Y. Otake, et al.
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 access to femoral head volume than does conventional straight drill.

<table>
<thead>
<tr>
<th>Conventional Rigid Drill Bit</th>
<th>Proposed Steerable Drill</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target Lesion Area</td>
<td>Lesion Area</td>
</tr>
</tbody>
</table>

Foreign Bodies in the Heart

<table>
<thead>
<tr>
<th>Causes</th>
<th>Symptoms</th>
<th>Conventional Treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thrombi, Shrapnel Iatrogenic</td>
<td>Cardiac Tamponade</td>
<td>Median Sternotomy</td>
</tr>
<tr>
<td></td>
<td>Hemorrhage</td>
<td>Cardiopulmonary Bypass</td>
</tr>
<tr>
<td></td>
<td>Arrhythmia</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Infection</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Shock</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Embolism</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Valve Dysfunction</td>
<td></td>
</tr>
</tbody>
</table>

Causes

Symptoms

Conventional Treatment

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

Retrieval Experiment Results
Thienphrapa et al. 2013
Vitreoretinal Microsurgery

Microsurgery Assistant Workstation

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

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

Patient-specific assessment and feedback

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
Elastography monitoring of ablations

Ex vivo

<table>
<thead>
<tr>
<th>B-mode image</th>
<th>Displacement image</th>
<th>Strain image</th>
<th>Gross pathology image</th>
</tr>
</thead>
<tbody>
<tr>
<td>ultrasound</td>
<td>elasticity</td>
<td>post-operation CT</td>
<td></td>
</tr>
</tbody>
</table>

patient 1

patient 2

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

Statistical Analysis and Decision Support

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

Model → Diagnose → Plan → Assess

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

Intervention
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

**Outer/Population Loop**

*Current Trial Practice*
- Data Collection
- Treatment Protocol
- Literature Search
- Journal Publication
- Data Analysis
- Patient Tx
- Follow up

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

**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

---

**Dosimetry (DVHs)**

**Segmented shapes**

**Dosimetry (DVHs)**

**Descriptor (OVHs)**

---

**Input to planning process**

**Quality control check**

---

**New patient PTV and critical structures**

**Specify Optimization Goals & Constraints**

**Optimize treatment parameters**

**Current planning process**

**Simulate treatment & visualize results**

**New patient OVH**

**Patient Database**

**Identify patients with similar OVHs**

**Best DVH for similar patients**

---

Applications Of Surgical Motion Models

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

The Language of Surgery
Hager, Khudanpur, Vidal + Chen, Lee, Ishii
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

Information-Intensive Interventional Suite

- Data Logging & Summary
- Logistics & scheduling
- PACS, other patient data bases
- Imaging systems (X-ray, US, CT, MRI, etc.)
- Assistant Workstation
- Surgeon Interfaces
- Robots
- OR video
- Anesthesia, vital signs, logistics, back table, etc.
The computer-integrated operating room

- **Patient Loop**
  - Video
  - "smart tool" sensors
  - Robotic devices

- **Process Loop**
  - Intraoperative information support
  - Preoperative images & other data
  - Intraoperative analysis

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

**Intraoperative information support**

**Preoperative images & other data**

**Intraoperative analysis**

**Outcome data**

**Complete record of intervention**
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