Acknowledgments

- This is the work of many people

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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
- Disclosures: 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, Virtusus 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.

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.
Human-machine partnership to fundamentally improve interventional medicine

Physicians

Patient Specific Assistance

Technology

Information

Statistical Process Improvement

Over 25 years ago: Robotic Joint Replacement Surgery

Manual Surgery

Robotic 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

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

Computer-Integrated Interventional Medicine

General/Multi-Patient Data
- Statistical anatomic atlases
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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.

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

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

Model → Diagnose → Plan → Intervention

Assess

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

Data courtesy of Terry Peters and Eric Ford
Combining prior knowledge with online images

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

Prior images & models (mostly 3D) → Computational process

New Images (2D, 3D) → Computational process

• Segmentation
• Registration
• Hybrid reconstruction

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 → Hip Osteotomy

2 X-ray Images → 2D/3D Registration

A “smart” sinus endoscopy assistant

Recovery of 3D anatomy from endoscopic video

• Dense point cloud recovery from untracked monocular endoscope video
• Registration to preoperative CT or statistical model
• Intraoperative navigation and surgical assistance

Navigation
Quantitative endoscopy Assistance Modes Learning & Training

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**

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

2. **Model**
3. **Diagnose**
4. **Plan**
5. **Patient-Specific Data**
   - Images, lab data, genomics
   - Clinical history
   - Models & plans
   - Etc.

6. **Assess**
7. **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, Deguet, Coune, Taylor, Sauer, Iorchidata, Masamune, Zinreich, 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,
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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, …
Example: Ultrasound-guided needle placement

Traditional ultrasound screen AND on-screen guidance overlay

As well as on-patient projection

TRUS Robot for Prostate Brachytherapy

Kazanzides, Iordachita, Burdette, Song, et al.

Current efforts:
- Integration with RadVision / RUF project
- Needle quick-release mechanism
- Intraoperative user interface (sterile touchscreen)

Prototype sterile touchscreen: Digital Dash
Prostate brachytherapy seed localization using combined photoacoustic and ultrasound imaging
Boctor/Kang/Prince (JHU), Burdette (AMS)

B-mode
PA-mode

MRI-guided Surgical Manipulator for Transperineal Prostate Interventions - Clinical Workflow

Patient ready on scanner table
Z-frame in position
Drape robot, attach needle guide

Slide in robot until hit Z-frame
Lock robot in place
Robot ready for targeting

NIH 2R01CA111288: C. Tempany, Iordachita, Fischer, Tokuda, Hata, …
Current dominant paradigm for interactive surgery

- **Physicians**
  - Master manipulator motions

- **Computer**
  - Teleoperator control
  - Safety monitoring
  - User console
  - Housekeeping

- **Technology**
  - Robot joint motions & state

- **Information**
  - Stereo video

Emerging paradigm (shared autonomy & assistant modes)

- **Physicians**
  - Master manipulator motions
  - Haptic feedback

- **Computer**
  - Teleoperator control
  - Virtual fixtures
  - Shared autonomy
  - Information fusion
  - Visualization
  - Smart tools & sensors
  - Safety monitoring, etc.

- **Technology**
  - Robot joint motions & state

- **Information**
  - Stereo video
Robotically Assisted Laparoscopic Ultrasound

• NIH STTR between CISST ERC and Intuitive Surgical
• Goals
  – Develop dexterous laparoscopic ultrasound instrumentation and software interfaces for DaVinci surgical robot
  – Produce integrated system for LUS-enhanced robotic surgery
  – Evaluate effectiveness of prototype system for liver surgery
• Approach
  – Custom DaVinci-S LUS tool
  – Software built on JHU/ISI “SAW” interface
• Status
  – Evaluation of prototype by surgeons

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: Under a license agreement between Galen Robotics, Inc. and the Johns Hopkins University, Dr. Taylor and the University are entitled to royalty distributions on technology related to technology described in the study discussed in this publication. Dr. Taylor also is a paid consultant to and owns equity in Galen Robotics, Inc. This arrangement has been reviewed and approved by the Johns Hopkins University in accordance with its conflict-of-interest policies.
A “smart” skull base surgical assistant

- Stereo Video
- 3D Point Cloud
- Patient CT
- Registered
  and updated
  real time
  model
- Tool tracking

Assistance Modes & Virtual fixtures
- Navigation
- Advanced Visualization
- Learning & Training

Max Li, Russ Taylor, Mathias Unberath, Francis Creighton, ...

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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

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.

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

Combined RCM Robot and Dexterous Manipulator
US Beacon (on tip)
3D TEE Probe

Workstation Computer
Philips 3D Ultrasound
Cone Beam CT (optional)

Retrieval Experiment Results
Thienphrapa et al. 2013
Vitreoretinal Microsurgery

Microsurgery Assistant Workstation
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 ➔ Assess ➔ Intervention

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

Ex vivo

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

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

Assess

Intervention

Credit: Boctor, Rivaz, Choti, Hager, 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

Outer/Population Loop

Current Trial Practice

Hypothetical Future Practice

Increased potential for data reuse
Publications with live data!
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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Information-Intensive Interventional Suite

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

- **Patient Loop**
  - "smart tool" sensors
  - video
  - robotic devices

- **Process Loop**
  - Complete record of intervention
  - Outcome data

- **Intraoperative analysis**
  - Preoperative images & other data

- **Manipulation assistance**

- **Postoperative analysis & process improvement**

- **Preoperative images & other data**

- **Complete record of intervention**

- **Outcome data**

- **Intraoperative information support**

- **Complete record of intervention**

- **Outcome data**

- **Postoperative analysis & process improvement**
The computer-integrated operating room

- Manipulation assistance
- Intraoperative information support
- Intraoperative analysis
- Preoperative images & other data
- Complete record of intervention
- Outcome data
- Postoperative analysis & process improvement
- Complete record of intervention
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- Manipulation assistance
- Intraoperative information support
- Intraoperative analysis
- Preoperative images & other data
- Complete record of intervention
- Outcome 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 academic 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
- 45 systems now deployed around the world
- 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