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-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
- 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, 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.

A short personal background: Emad Boctor
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

Statistical Process Improvement
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 → Assess → Intervention

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

Combining prior knowledge with online images

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

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

Computational process:
- Segmentation
- Registration
- Hybrid reconstruction

Video: JH Yao, 2002

Applications:
- Intervention planning
- Intervention guidance & visualization
- Biomechanical analysis

Applications:
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- Biomechanical analysis

Deformable 2D/3D Registration to Statistical Atlas

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

Examples: R. Taylor, J. Yao, O. Sadowsky, G. Chintalapani, O. Ahmad, …
Model Completion, Given Partial CT + X-rays


- Prior statistical information (atlas)
- Partial CT Scan
- 2 X-ray Images
- Computational process
  - Atlas Extrapolation
  - 2D/3D Registration
- Patient-specific model
- Hip Osteotomy
  - Biomechanical analysis
  - Intraoperative registration

Information
- Patient-specific Information
  - (Images, lab results, genetics, etc.)

Procedure Planning
- Model
- Plan
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

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.

- **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
Procedure Execution

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Procedure Execution

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Image-guided needle placement

Masamune, Fichtinger, Iordachita, ...
Okamura, Webster, ...
Krieger, Fichtinger, Whitcomb, ...

Fichtinger, Kazanzides, Burdette, Song ...
Iordachita, Fischer, Hata ...
Taylor, Masamune, Susil, Patriciu, Stoianovici, ...

Current dominant paradigm for interactive surgery

Physicians
Master manipulator motions

Stereo video

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

Robot joint motions & state

Technology

Information
**Emerging paradigm (shared autonomy & assistant modes)**

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

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

**Computer**
- Stereo video
- Robot joint motions & state

**Information**
- 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

**Robotically Assisted Laparoscopic Ultrasound**

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- Approach
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- 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

Cadaver Study: Sinus Surgery with Virtual Fixtures

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, ....

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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

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**Single Port Access Surgery**

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

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=jlJvycKA6xQ

 Intuitive Surgical Sp
 https://www.youtube.com/watch?v=jm63JdTrp4

Treatment of Osteolysis Through the Acetabular Implant Screw Holes

Sefati et al, IEEE TRO, 2021
Curved Drilling of the Femoral Head

- 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

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

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Beating Heart MIS with 3D US Guidance

Paul Thienphrapa, Aleksandra Popovic, Russell Taylor

Diagram showing ultrasound guidance, combined RCM robot, dexterous manipulator, TEE, US beacon, and cone beam CT.
Retrieval Experiment Results

PHILIPS

Thienphrapa et al. 2013

Vitreoretinal Microsurgery


Alcon Vitreosurgery Instrument

www.eyemdlink.com
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

Intervention

Assess

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

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, Chotti, Hager, et al.
**Image-Guided Radiation Therapy - Prostate Brachytherapy**

- **Goals:** Provide immediate feedback for use in executing and monitoring implant procedure and for intra-operative treatment optimization.
- **Issues / Themes:** Online imaging, real-time implant reconstruction and multi-modal image registration, visualization/feedback, and dosimetry optimization.

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**Prostate brachytherapy seed localization using combined photoacoustic and ultrasound imaging**

Boctor/Kang/Prince (JHU), Burdette (AMS)

B-mode          PA-mode
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
- Patient Tx
- Literature Search
- Data Analysis
- Journal Publication

**Hypothetical Future Practice**
- Data Collection
- Patient Tx
- Literature Search
- Data Analysis
- Journal Publication
- Publication of Data to DB

Stop & Start Over

**Increased potential for data reuse**

**Publications with live data!**

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**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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** Dosimetry (DVHs)**
- Segmented shapes

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Applications Of Surgical Motion Models

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


**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

Assistant Workstation

Imaging systems
- X-ray, US,
- CT, MRI, etc.

Surgeon Interfaces

OR video
Anesthesia, vital signs, logistics, back table, etc.
Robots

The computer-integrated operating room

Patient Loop

Manipulation assistance
Intraoperative information support
Intraoperative analysis

"smart tool" sensors
robotic devices

Postoperative analysis & process improvement
Complete record of intervention
Outcome data

Process Loop
Preoperative images & other data

2021 R. H. Taylor
Engineering Research Center for Computer Integrated Surgical Systems and Technology
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

cisst libraries and Surgical Assistant Workstation
https://trac.lcsr.jhu.edu/cisst

Peter Kazanzides, Simon P. DiMaio, Anton Deguet, and many more
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
- 42 systems now deployed around the world
- [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