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- 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.
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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, Virtusoso 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

- Emad Boctor received Master’s and Doctoral degrees in 2004 and 2007 from the Computer Science Department of Johns Hopkins University.
- In 2007, he joined both The Russell H. Morgan Department of Radiology and Radiological Science and the Whiting School of Engineering, where he initiated a research program in the field of advanced ultrasound imaging.
- Since 2009, founder and director of the Medical Ultrasound Imaging and Intervention Collaboration (MUSiC) research laboratory.
- Dr. Boctor’s research focuses on brain imaging, early detection of aggressive cancer, and image-guided therapy and surgery, a subject in which he has authored and co-authored over 78 peer-reviewed manuscripts and 150 conference articles, has filed more than 40 pending and issued patents, and has been recognized with numerous awards and fellowships including the National Science Foundation CAREER award.
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
- Technology
- Information
- Patient Specific Assistance

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

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
- 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

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 BCE

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
- 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

**Video:** Blake Lucas, “SpringLS...”, MICCAI 2011 & subsequent papers. Data courtesy of Terry Peters and Eric Ford

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**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) → Partial CT Scan → 2 X-ray Images

Computational process
- Atlas Extrapolation
- 2D/3D Registration

Patient-specific model

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

Photo: Integrated Surgical Systems
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
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,
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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

Real-time multi-modal fusion

As well as on-patient projection

TRUS Robot for Prostate Brachytherapy
Kazanzides, Iordachita, Burdette, Song, et al. NSF SECO 1246356

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

Robot clinical trial

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

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

Robot joint motions & state

Technology

Emerging paradigm (shared autonomy & assistant modes)

Physicians
- Master manipulator motions
- Haptic feedback

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

Robot joint motions & state

Technology
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.
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

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=jlvycKA6xQ

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


APL

Curved Drilling of the Femoral Head

Alambeigi, Armand, et al.

S-Shape and multiple branch curved-drilling

Curved-Drilling Experiments on human cadaver specimens

**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)

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**Beating Heart MIS with 3D US Guidance**

Paul Thienphrapa, Aleksandra Popovic, Russell Taylor

- Workstation Computer
- Philips 3D Ultrasound
- Cone Beam CT (optional)
- US Beacon (on tip)
- Combined RCM Robot and Dexterous Manipulator
- 3D TEE Probe
- Foreign Body
- Dexterous Manipulator

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Retrieval Experiment Results

Thienphrapa et al. 2013

Vitreoretinal Microsurgery

PHILIPS
Microsurgery Assistant Workstation

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

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

B-mode image  Displacement image  Strain image  Gross pathology image

ultrasound  elasticity  post-operation CT

patient 1

patient 2

Credit: Boctor, Rivaz, Choti, 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.


Prostate brachytherapy seed localization using combined photoacoustic and ultrasound imaging
Boctor/Kang/Prince (JHU), Burdette (AMS)

B-mode

PA-mode
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
- Intervention

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

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
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
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


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

- Surgeon Interfaces

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

OR

The computer-integrated operating room

- Patient Loop
  - Manipulation assistance
  - "smart tool" sensors
  - Intraoperative information support
- Intraoperative analysis

- Process Loop
  - Preoperative images & other data
  - Complete record for instruction

- Postoperative analysis & process improvement
- Outcome data

- Robotic devices
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**

- Video
- "Smart tool" sensors
- Robotic devices

Intraoperative information support

Preoperative images & other data

Complete record of intervention

Outcome data

Postoperative analysis & process improvement

The computer-integrated operating room

- **Manipulation assistance**
- **Intraoperative information support**
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- Video
- "Smart tool" sensors
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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
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/

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