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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
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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 (MUSiiC) 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

Patient Specific Assistance

Technology

Information

Statistical Process Improvement
Over 25 years ago: Robotic Joint Replacement Surgery

Emerging: Information-Augmented Robotic Surgery


Experimental System: not for clinical use
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
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
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

- Segmentation
- Registration
- Hybrid reconstruction

Patient-specific model

Applications

- Intervention planning
- Intervention guidance & visualization
- Biomechanical analysis

Video: JH Yao, 2002

Prior images & models (mostly 3D) → New Images (2D, 3D)
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 → 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.

- **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, Deqaee, Coome, Taylor, Sauer,
Iorchidate, Masamune, Griech, Fichtinger, …
Procedure Execution

• Highly procedure-specific
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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, …
Current dominant paradigm for interactive surgery

- Physicians
- Master manipulator motions
- Stereo video
- Computer
  - Teleoperator control
  - Safety monitoring
  - User console
  - Housekeeping
- Robot joint motions & state

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
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, ….

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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.

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=jlvycKA6xQ

Intuitive Surgical Sp
https://www.youtube.com/watch?v=jm63JdTrp4
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
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)
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
OCT Display
Force and OCT sensing tools
FBG Interrogator
EyeRobot2
Audio Output
Stereo video Microscope
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, Hagen, 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.

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

Intervention

Model
Diagnose
Plan
Assess
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
  - Data Analysis
  - Journal Publication
  - Patient Tx
  - Follow up

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

- 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

**Quality control check**
- **Current planning process**
- **Input to planning process**
- **New patient PTV and critical structures**
- **Identify patients with similar OVHs**
- **New patient OVH**

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

**Best DVH for similar patients**
- **Descriptor (OVHs)**

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
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

Automatic Segmentation of Strokes in Nasal Septoplasty

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

- Imaging systems: X-ray, US, CT, MRI, etc.
- OR video
- Assistant Workstation
- Logistics & scheduling
- Data Logging & Summary
- PACS, other patient data bases

Surgeon Interfaces

Robots

Anesthesia, vital signs, logistics, back table, etc.
The computer-integrated operating room

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

The complete record of intervention supports and improves the outcomes of surgical procedures.
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