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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


Experimental System: not for clinical use
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
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

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

Partial CT Scan → 2D/3D Registration → Hip Osteotomy
+ Biomechanical analysis
+ Intraoperative registration

Information

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

Procedure Planning

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Engineering Research Center for Computer Integrated Surgical Systems and Technology
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

Photos: Mehran Armand

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

Photos: Mehran Armand
**Procedure Execution**

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

- **Model** → **Diagnose** → **Plan** → **Intervention**

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

- **Assess**

---

**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

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Masamune, Fischer, Deguet, Coons, Taylor, Sauer, Itzkovitz, Masamune, Zinreich, Fichtinger, …
Procedure Execution

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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, ...

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)

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

Clear Guide ONE

CG1 enables more doctors to perform more needle-based procedures more places, more effectively and more quickly.
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: Tempany, Iordachita, Fischer, Tokuda, Hata, ...

Information-enhanced robotic surgery

augmented reality displays imaging

safety barriers shared control “virtual fixtures”

SAW
Robots for Head and Neck Surgery

- Collaboration with JHU Department of Otolaryngology
- Robot to manipulate flexible endoscopes (RoboELF)
  - Prototype for flexible laryngoscope
  - “No significant risk” from FDA; IRB approved at JHU
- Steady-hand robot for head and neck surgery (REMS)
  - Initial targets: laryngeal, sinus, ear, open microsurgery
  - Readily adapted for spine, brain, other microsurgery
  - First prototype constructed

A Robotic Assistant for Trans-Oral Surgery: The Robotic Endo-Laryngeal Flexible (Robo-ELF) Scope

K. Olds, A. Hillel, E. Cha, J. Kriss, A. Nair, L. Akst, J. Richmon, R. Taylor

- Goals
  - Develop clinically usable robot for manipulating flexible endoscope in throat and airways
  - Permit bimanual surgery
  - Manipulation of ablation catheter
- Approach
  - Simple hardware for manipulating unmodified flexible scope
  - Simple joystick control
  - Platform for image guidance
- Status
  - “No significant risk” determination from FDA
  - IRB approved clinical trial starting
Robo-ELF Scope Clinical Prototype

- FMEA
- Extensive documentation
  - User manual etc.
- New scope holder and draping system
- FDA approved as NSR
- JHU Clinical engineering approval
- JHU IRB approval
- Clinical study starting this summer

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.

REMS Typical Applications

Laryngeal / Vocal Cord

Open Microsurgery

Image-guided sinus surgery with virtual fixtures

Other applications include:
- Otology
  - Stapes surgery
  - Mastoidectomy
  - Cochlear implant
- Craniotomy
- Spine
- Hand
- …
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**
  - Evaluation of prototype ongoing
  - Licensed to industry partner

- **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=jlvyvKdA6xQ

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

Minimally-Invasive Osteolysis Curettage

M. Armand, R. Taylor, M. Kutzer, R. Murphy, S. Segretti, 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

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

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

Ultrasound Elastography with DaVinci
(Boctor, Billings, Taylor)

Human-robotic collaboration for in-vivo detection of tumors and monitoring of therapy
(Research DaVinci Application – Not for Human Use)
Vitreoretinal Microsurgery

Microsurgery Assistant Workstation

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

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

Model
Diagnose
Plan

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

Assess

Intervention

Statistical Analysis and Decision Support

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

Assistant Workstation

Surgeon Interfaces

OR video

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

Robots

The computer-integrated operating room

- Manipulation assistance
- Intraoperative information support
- Intraoperative analysis
- Preoperative images & other data
- Outcome data
- Complete record information

Patient Loop

"smart tool" sensors

Process Loop

Preoperative analysis & process improvement

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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

- Video
- "Smart tool" sensors
- Robotic devices

The computer-integrated operating room

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

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

- Peter Kazanzides, Simon P. D'Malio, Anton Deguet, and many more
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/

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