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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
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

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**Image-based modeling & analysis**

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

**Patient-Specific Data**
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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

Prior images & models (mostly 3D) → Patient-specific model

New Images (2D, 3D) → 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

2 X-ray Images

Computational process

Atlas Extrapolation

2D/3D Registration

Hip Osteotomy
- Biomechanical analysis
- Intraoperative registration

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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.

- **Intervention**

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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

Masamune, Fischer, Deguet, Coome, Taylor, Sauer, Iorchidata, Masamune, Zinreich, Fichtinger, ...

Solomon et al.
Okamura et al.
Procedure Execution

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  – Image Overlay
• **But robots can transcend human limitations**
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  – 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

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**Image-guided needle placement**

- Masamune, Fichtinger, Iordachita, ...
- Okamara, Webster, ...
- Krieger, Fichtinger, Whitcomb, ...
- Fichtinger, Kazanzides, Burdette, Song, ...
- Iordachita, Fischer, Hata, ...
- Taylor, Masamune, Susil, Patriciu, Stoianovic, ...
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
Clear Guide ONE

CG1 enables more doctors to perform more needle-based procedures more places, more effectively and more quickly.
Information-enhanced robotic surgery

* augmented reality displays imaging
* safety barriers
* shared control
  “virtual fixtures”

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

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


REMS Typical Applications

Laryngeal / Vocal Cord

Open Microsurgery

Other applications include:
- Otology
  - Stapes surgery
  - Mastoidectomy
  - Cochlear implant
- Craniotomy
- Spine
- Hand
- …

Image-guided sinus surgery with virtual fixtures
Cadaver Study: Sinus Surgery with Virtual Fixtures

Robot-assisted Sinus Surgery Cadaver Demonstration

K. Olds, M. Balicki, M. Ishii, R. Taylor
Engineering Research Center for Computer Integrated Surgical Systems and Technology
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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, ….
**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**

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=jIvycKAI6xQ

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

(Actis Dato, 2003)
(LeMaire, 1999)

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Beating Heart MIS with 3D US Guidance

Paul Thienphrapa, Aleksandra Popovic, Russell Taylor

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

Thienphrapa et al. 2013
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
- Stereo video Microscope
- OCT Display
- 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** → **Assess** → **Intervention**

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

Ex vivo ultrasound elasticity post-operation CT

B-mode image Displacement image Strain image Gross pathology image

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
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
- Journal Publication
- Data Analysis
- Stop & Start Over

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

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

New patient PTV and critical structures

Input to planning process

Quality control check

Best DVH for similar patients

Identify patients with similar OVHs

Descriptor (OVHs)

Descriptor (OVHs)

Descriptor (OVHs)

Descriptor (OVHs)

Descriptor (OVHs)

Descriptor (OVHs)

Descriptor (OVHs)

Descriptor (OVHs)

Descriptor (OVHs)

Descriptor (OVHs)

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.

G. Hager, et al.

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The Language of Surgery

Hager, Khudanpur, Vidal + Chen, Lee, Ishii

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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


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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


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OR Workflow Observation and Analysis
N. Navab et al.

Information-Intensive Interventional Suite

Data Logging & Summary
Logistics & scheduling
PACS, other patient databases

Imaging systems
- Xray, US,
- CT, MRI, etc.

Assistant Workstation

Surgeon Interfaces

Robots

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

OR video
The computer-integrated operating room

- **Patient Loop**
  - Video
  - "smart tool" sensors
  - Intraoperative analysis
  - Preoperative images & other data
  - Manipulation assistance

- **Process Loop**
  - Complete record of intervention
  - Outcome data
  - Postoperative analysis & process improvement

- **Robotics Devices**

**Intraoperative information support**

**Postoperative analysis & process improvement**

**Complete record of intervention**

**Outcome data**

**Preoperative images & other data**

**Manipulation assistance**

**Intraoperative analysis**

**Video**

**"smart tool" sensors**

**The computer-integrated operating room**

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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
- Outcome data
- Complete record of intervention
- Postoperative analysis & process improvement
- Complete record of intervention

Preoperative images & other data

Manipulation assistance

Intraoperative information support

Intraoperative analysis

Preoperative images & other data

Outcome data

Complete record of intervention

Postoperative analysis & process improvement
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/](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