Acknowledgments

- **This is the work of many people**

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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

Model \[\rightarrow\] Diagnose \[\rightarrow\] Plan

Patient-Specific Data

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

Assess \[\rightarrow\] 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

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

Model
Diagnose
Plan
Assess

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

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

Data courtesy of Terry Peters and Eric Ford
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) → Computational process → Patient-specific model

Partial CT Scan → Atlas Extrapolation → 2D/3D Registration

2 X-ray Images → Hip Osteotomy

• Biomechanical analysis
• Intraoperative registration

Information

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

Procedure Planning

Virtual fixture

Model

Plan

Medical Arrows

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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

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

- 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, Iorchida, Masamune, Zinreich, Fichtinger, …
Procedure Execution

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- Don’t always have a robot
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Procedure Execution

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• But robots can transcend human limitations
  – to make procedures less invasive,
  – more precise,
  – more consistent,
  – and safer

P. Kazanzides, T. Haiddeger, T. Xia, C. Baird, G. Jallo, N. Hata, …

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

Information-enhanced robotic surgery

augmented reality displays imaging

safety barriers shared control "virtual fixtures"

SAW
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

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: Prof. Taylor is a paid consultant to and has equity in Galen Robotics and also may receive income from patent royalties from Galen
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=jlvycKA6xQ

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 access to femoral head volume than does conventional straight drill.
**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
- US Beacon (on tip)
- 3D TEE Probe
- Foreign Body
- Workstation Computer
- Philips 3D Ultrasound
- Philips 3D Ultrasound
- Cone Beam CT (optional)
Retrieval Experiment Results

![Graph showing 3D Foreign Body Position in Robotic Retrieval]

**Vitreoretinal Microsurgery**

![Image of surgical instruments and ophthalmologist]

*British Journal of Ophthalmology 2004 - Akifumi Ueno et al*

*www.eyemdlink.com*

**PHILIPS**

Thienphrapa et al. 2013
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**

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

**Assess**

---

**Elastography monitoring of ablations**

Ex vivo

<table>
<thead>
<tr>
<th>B-mode image</th>
<th>Displacement image</th>
<th>Strain image</th>
<th>Gross pathology image</th>
</tr>
</thead>
</table>

ultrasound  elasticity  post-operation CT

patient 1

patient 2

Credit: Boctor, Rivaz, Chotti, Hager, et al.
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
- Follow up
- Literature Search
- Journal Publication

Stop & Start Over

Hypothetical Future Practice

- Data Collection
- Patient Tx
- Follow up
- Literature Search
- Journal Publications
- Publication of Data to DB
- Data Analysis and 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
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

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**

- **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.**

**OR video**

**Robots**

**The computer-integrated operating room**

- **Patient Loop**
  - Video
  - "smart tool" sensors
  - Robotic devices

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

**Intraoperative analysis**

**Preoperative images & other data**

**Manipulation assistance**

**Intraoperative information support**

**Outcome data**
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**

Robotic devices, sensors, and video inputs are integrated into the system for comprehensive analysis and monitoring during and after the operation.
The computer-integrated operating room

Manipulation assistance

Intraoperative information support

Intraoperative analysis

Preoperative images & other data

Complete record of intervention

Postoperative analysis & process improvement

Outcome data

The computer-integrated operating room

Preoperative images & other data

Intraoperative information support

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. 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 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