Acknowledgments

- This presentation reflects the contributions of many collaborators and colleagues from the CISST ERC and elsewhere. They are too many to name here, but their contributions are gratefully acknowledged.
- Partial funding or other support for the work presented likewise was provided by many sources, including
  - National Science Foundation, National Institutes of Health, Department of Defense, National Institute of Science and Technology
  - Siemens, Philips, Intuitive Surgical, General Electric, Acoustic MedSystems, Integrated Surgical Systems, Carl Zeiss Meditec, Alcon, and other Industry partners of the CISST ERC
  - Johns Hopkins University internal funds
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.
This Paradigm has not changed since Imhotep’s day

But medical robots and computer-integrated interventional systems will make it much more effective

Example: Robotic Joint Replacement Surgery

Manual Surgery

Robotic Surgery
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

Engineering Research Center for Computer Integrated Surgical Systems and Technology (CISST ERC)
The CISST ERC is developing a family of surgical systems that combine innovative algorithms, robotic devices, imaging systems, sensors, and human-machine interfaces to work cooperatively with surgeons in the planning and execution of surgical procedures.

Areas of Research
- Robotic surgical assistants
- Image-guided interventional systems
- Focused interdisciplinary research in algorithms, imaging, robotics, sensors, human-machine systems

Institutions & Funding
- Johns Hopkins, MIT, CMU, BWH, Harvard, Penn, Morgan State, Columbia
- Years 1-11: NSF = $32.7M; Total = ~$64.7M
- In-kind support = ~$13.9M

http://www.cisst.org
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:
- Segmentation
- Registration
- Hybrid reconstruction → Patient-specific model

Prior images & models (mostly 3D) → New Images (2D, 3D) → Video: JH Yao, 2002

Applications:
- Intervention planning
- Intervention guidance & visualization
- Biomechanical analysis

Intraoperative Overlay of CT model onto laparoscopic video

Stereo Video → Preoperative CT + Surgical plan data → Computational process:
- Reconstruct surface from video
- Register surface to preoperative model and resection plan → Visualization

Information Overlay in Endoscopic Skull Base Surgery
Siewerdsen, Hager, Mirotta, et al.


Deformable 2D/3D Registration to Statistical Atlas

Prior statistical information (atlas) → Computational process → Patient-specific model

X-ray projection images

Applications
- Orthopaedic surgery planning
- Biomechanical analysis
- Hybrid reconstruction

Examples: R. Taylor, J. Yao, O. Sadowsky, G. Chintalapani, O. Ahmad, ...
**2D/3D Registration – Hip Model**

- Registration with truncated images
  - FOV: 160mm
  - Three views
- Avg surface registration accuracy: 2.15 mm

![Atlas projections overlaid on DRR images after registration](Image)

![2D/3D deformable registration](Image)

Chintalapani et al. CAOS 2009

**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
Bone Biomechanical Properties from limited DXA Images

JHU: Omar Ahmed, Ofri Sadowsky, Russell Taylor
U. Erlangen: Klaus Engelke
BIDMC, Boston: Mary Bouxsein
Inst. of Aging Research, Boston: David Karasik
Hologic, Inc.: Krishna Ramamurthi, Kevin Wilson

Prior statistical information (atlas) → Computational process → Patient-specific model ("VXA" = virtual QCT)

DXA Images

Applications
• Biomechanical analysis

Whole Body Atlasing

Blake Lucas, Unifying Deformable Model Representations with New Geometric Data Structures, Ph.D. Thesis in Computer Science, Johns Hopkins University, July 2012

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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

- 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, Ziemich, Fichtinger, …

Solomon et al.
Okamura et al.
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

Intuitive Surgical.

Simaan et al.

Procedure Execution

• Highly procedure-specific
• Don’t always have a robot
  – Surgical Navigation
  – Image Overlay
• But robots can transcend human limitations
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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
Information-enhanced robotic surgery

- augmented reality displays imaging
- safety barriers shared control "virtual fixtures"
- SAW

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

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**
  - In process of obtaining IRB approval for clinical use
New Robot for Head and Neck Surgery


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)
Minimally-Invasive Osteolysis Curettage

Planning Workstation
- Patient modeling
- FEM analysis
- Plan optimization
- FEM updates
- Plan revisions

Preoperative CT Data
Preoperative Workstation
- 2D-3D registration
- Optical tracking
- Work flow control
- Model updates
- Human Interface
- 3D Visualization
- Robot Control

Treatment updates
Plan & Images

Intraoperative Workstation
- 2D-3D registration
- Optical tracking
- Work flow control
- Model updates
- Human Interface
- 3D Visualization
- Robot Control

C-Arm
Optical Tracker

Fiducial Attachment
Haptic Device

Positioning Robot
**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

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

Paul Thienphrapa, Aleksandra Popovic, Russell Taylor

- Foreign Body
- 3D TEE Probe
- Dexterous Manipulator
- Combined RCM Robot and Dexterous Manipulator
- Workstation Computer
- Philips 3D Ultrasound
- US Beacon (on tip)
- 3D TEE Probe
- Foreign Body
- Cone Beam CT (optional)
Beating Heart MIS with 3D US Guidance
Paul Thienphrapa, Aleksandra Popovic, Russell Taylor

Track and Observe … then ambush

Beating Heart Phantom

iE33 Ultrasound System

Snake Robot

X7-2t TEE Probe

Lars Robot

Paul Thienphrapa, March 2013
Experimental Procedure

1. Register robot to US images
2. Teleoperate robot to heart; Set RCM mode
3. Select foreign body in images
4. Track foreign body; Compute capture location
5. Guide robot for capture (automatic)

Retrieval Experiment Results
Retrieval Experiment Results

• Success criterion: capture within 30 seconds

• Spatial probability
  – Success: 14/17 (82.4%)
  – Observation: 29.6 ± 6.9 sec
  – Waiting: 3.7 ± 2.0 sec
  – Total: 97.7 ± 21.6 sec

• Dwell time
  – Success: 5/5 (100%)
  – Observation: 54.3 ± 33.1 sec
  – Waiting: 2.2 ± 1.5 sec
  – Total: 124.5 ± 68.4 sec

• Failures
  – Reason: Motion changed after the capture location computed
  – Solution: Adaptive retry

  • Large time variance possibly due to irregular motion

  • Times of 2-3 minutes implies potential for improvement

  • Visit frequency not tested

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

Research DaVinci Application – Not for Human Use

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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)

Video-CBCT guidance for TORS

Cadaver Study

Example: Human-Machine Collaborative Surgery
Nicholas Padoy, Greg Hager (IROS 2011)
Dynamic Augmented Reality for Sensory Substitution in Robot-Assisted Surgical Systems

A. Okamura, T. Yamamoto et al.

Vitreoretinal Microsurgery


Alcon Vitreosurgery Instrument

www.eyemdlink.com
Microsurgery Assistant Workstation

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

In-Vivo Experiments

- Overall System Performance
- System Ergonomics
- Collect Data
  - Robot / Force / OCT
  - Video / Audio
Closed Loop Interventional Medicine

Patient-specific Evaluation

Elastography monitoring of ablations

Ex vivo

ultrasound
elasticity
post-operation CT

Credit: Boctor, Rivaz, Choti, Hager, et al.
Reconstruction of injected cement from sparse x-rays


Example: Cadaver study with soft tissue and 4 difference images

Injected femur + pre-injection images

4-8 post-injection projection images

Ground Truth

New method

Silhouette method
Reconstruction with Difference Images

Ground Truth
Visual Hull (4 images)
SxMAC (4 images)
X-Ray Image

Ground Truth
Visual Hull (8 images)
SxMAC (8 images)
Difference Image

Closed Loop Interventional Medicine

Patient-specific Interventional Medicine
Patient-specific Information
(Images, lab results, genetics, etc.)
General information
(anatomic atlases, statistics, rules)

Information

Model ➔ Plan ➔ Action

Patient-specific loop
Patient-specific Evaluation

Process Loop
Statistical Analysis

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Engineering Research Center for Computer Integrated Surgical Systems and Technology
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
“The language of surgery”
Statistical learning of surgical gestures

Hager, et al.

Information-Intensive Interventional Suite

- Data Logging & Summary
- Logistics & scheduling
- PACS, other patient data bases

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

- Assistant Workstation

- OR video

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

Robots
Surgical Assistant Workstation

Use case: Da Vinci “Toolkits”

- 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
  - Controller power/packaging – WPI
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