Medical Robotics and Computer-Integrated Interventional Systems: Integrating Imaging, Intervention, and Informatics to Improve Patient Care

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  – Johns Hopkins University internal funds
Goal: Human-machine partnership to fundamentally improve interventional medicine

20 years ago: Robotic Joint Replacement Surgery

Taylor, Kazanzides, Paul, Mittelstadt, et al.
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Engineering Research Center for Computer Integrated Surgical Systems and Technology
Emerging: Information-augmented robotic surgery


Experimental System: not for clinical use

Closed Loop
Interventional Medicine

Information

Patient-specific Evaluation

Patient-specific loop

Process Loop

Statistical Analysis

Model

Plan

Action

General information (anatomic atlases, statistics, rules)

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

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Engineering Research Center for Computer Integrated Surgical Systems and Technology
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
- Now mix of NSF, NIH, Industry through LCSR

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

Video: Blake Lucas, "SpringLS...", MICCAI 2011 & subsequent papers. Data courtesy of Terry Peters and Eric Ford

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

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
2D/3D deformable registration

Chintalapani et al. CAOS 2009
Model Completion, Given Partial CT + X-rays


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

Partial CT Scan → Computational process: 2D/3D Registration → Hip Osteotomy

- Biomechanical analysis
- Intraoperative registration

Information Overlay in Endoscopic Skull Base Surgery

Siewerdsen, Hager, Mirota, et al.

Registration of intraoperative data to preoperative models

- Want to know registration from tracker to CT space
  - Provides tool positions relative to CT
- Data sources for registration
  - Tracked ultrasound
  - Tracked (or calibrated) range data


Paired Point Algorithms Outline

- Iterative Closest Point (ICP)
  - the standard algorithm
  - position-only method
  - isotropic (Gaussian) noise model
- Iterative Most Likely Point (IMLP)
  - position-only method
  - generalized Gaussian noise model
- Iterative Most Likely Oriented Point (IMLOP)
  - position & orientation method
  - isotropic orientation (Fisher) and position (Gaussian) noise model
- Generalized IMLOP
  - extension of IMLOP
  - generalize orientation (Kent) and position (generalized Gaussian) noise model

Experiments

Performance comparison of IMLOP vs. ICP was made through a simulation study using a human femur surface mesh segmented from CT imaging.

- source shape created by randomly sampling points from the mesh surface (10, 20, 35, 50, 75, and 100 points tested)
- Gaussian [wrapped Gaussian] noise added to the source points (0, 0.5, 1.0, and 2.0 mm [degrees] tested)
- Applied random misalignment of [10,20] mm / degrees
- 300 trials performed for each sample size / noise level
- Registration accuracy (TRE) evaluated using 100 validation points randomly sampled from the mesh
- Registration failures automatically detected using threshold on final residual match errors

ICP: threshold on position residuals only
IMLOP: threshold on position & orientation residuals


Average TRE of successful registrations and registration failure rates across all sample sizes for noise levels of 1 (A) and 2 (B) mm [degrees].

Registration failure threshold set to twice the noise level for both position and orientation.

Experiments

Results from 300 trials within a single sample size (75 points) and noise level (1.0 mm [degree]). NOTE: improved accuracy and failure detection capability for IMLOP.

Widely distributed TRE follows drop in residual error

Sharp drop in TRE accompanies drop in residual error


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
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
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• But robots can transcend human limitations
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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

To be continued …
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PART B

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Image-guided needle placement

Masamune, Fichtinger, Iordachita, ...
Okamura, Webster, ...
Krieger, Fichtinger, Whitcomb, ...
Fichtinger, Kazanzides, Burdette, Song ...
Iordachita, Fischer, Hata ...
Taylor, Masamune, Susil, Patriciu, Stolano...
Information-enhanced robotic surgery

- Augmented reality displays imaging
- Safety barriers
- Shared control
- "Virtual fixtures"

Video-CBCT guidance for TORS

Video-CBCT guidance for TORS


Experimental System: not for clinical use

da Vinci Sp

- Research daVinci model, approved by FDA, April 2014
- Single-incision, 25 mm trocar
- Articulated camera
- 3 articulated endo-wrist instruments
- Entry Guide Manipulator (EGM)
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
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.

Beating Heart MIS with 3D US Guidance

Paul Thienphrapa, Aleksandra Popovic, Russell Taylor
Retrieval Experiment Results

Thienphrapa et al. 2013
Large Lumen, Dexterous Snake for MIS

- Joint project with JHU APL
- Innovative fabrication process completely isolates drive cables
- Current prototypes
  - 2 DoF (C-bend) and 4DoF (S-bend)
  - Nitinol structure with high stiffness
  - 6 mm OD; Large 4 mm lumen allows insertion of surgical instruments
- Initial application: minimally-invasive curettage of osteolytic lesions

Minimally-Invasive Osteolysis Curettage
Large Lumen, Dexterous Snake for MIS

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Minimally-Invasive Osteolysis Curettage

Image-based 2D-3D Registration

Interpret 3D objects from 2D image via simulation of projection

<table>
<thead>
<tr>
<th>Target object</th>
<th>Prior information</th>
<th>Parameters to estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rigid</td>
<td>Bone</td>
<td>6 DoF</td>
</tr>
<tr>
<td>Piecewise-Rigid</td>
<td>Manipulators</td>
<td>6 DoF + Joint angles</td>
</tr>
<tr>
<td>Deformable</td>
<td>Soft tissue</td>
<td>Mode of deformation, Physical constraint</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6 DoF + Deformation field (control points or mode weights)</td>
</tr>
</tbody>
</table>
**Proposed Solution: Piecewise Rigid 2D-3D Registration**

Maximize similarity between simulated and real image

![Diagram showing the process of Piecewise Rigid 2D-3D Registration](image)

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**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)

Direct 3D Ultrasound to Video Registration
Using Photoacoustic Effect
The Johns Hopkins University

Advantages of PA system
- No wires
- No markers or sensors
- No Calibration Process
- Directly register video and 3D Ultrasound

Literature shows registration errors of approximately 3mm
Our synthetic and ex vivo tissue phantom experiments show submillimeter errors!
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 pending 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
  - In process of obtaining IRB approval for clinical use
Steady Hand Robot for Head and Neck Microsurgery


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To be continued …
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PART C

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Vitreoretinal Microsurgery

www.eyemdlink.com
Alcon Vitreosurgery Instrument
Engineering Research Center for Computer Integrated Surgical Systems and Technology
Microsurgical Assistant for Retinal Surgery

Goals
- Develop technology addressing fundamental limitations in retinal microsurgery
- Integrate into comprehensive system
- Validate performance
- Transfer to clinical use

Team
- **SoM**: J. Handa, P. Gehlbach, S. Sunshine, N. Cutler
- **CMU**: C. Riviere, B. Becker, R. MacLachlan

Current Funding
- NIH BRP5 R01 EB007969 (Taylor)
- NIH R01 EB000526 (Riviere)
- NIH R01 EY021540 (Kang)
In-Vivo Experiments

- Overall System Performance
- System Ergonomics
- Collect Data
  - Robot / Force / OCT
  - Video / Audio
Tool and Retina Tracking

MICRON active tremor cancellation device
Cameron Riviere, Robert McLaughlin, B. Becker et al. (CMU)

- Handheld device
- Sense tremulous motion
- Actively move to compensate
- BRP Research goals:
  - Incorporate “endpoint sensing” from vision & other sensors
  - Virtual fixtures
  - Improved device for eventual clinical use
  
  Stay within volume
  Trace a circle
  Add End Soft Fixtures
  Add End Hard Fixtures

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**JHU Steady Hand “Eye Robot”**


- Highly precise robot
- Hands-on cooperative control or teleoperation
- Several generations in lab
- Precise, stable platform for developing “smart” surgical instruments and sensors
- Virtual fixtures and advanced control

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**Force Sensing Surgical Instruments**

- Incorporate fiber optic force sensors into 0.5 mm diameter surgical tools
- 0.25 mN force sensitivity
2-DOF Force Sensing Tools

Fiber Bragg Grating (FBG sensors)

FBGs

FBG Ø125 μm

FBG sensors

2-DOF Pick Tool

2-DOF Forceps Tool

He et al. 2012

3-DOF Force Sensing Pick Tool

Distal force sensing segment

Quick release mechanism

Stainless steel tube Ø0.5mm

Nitinol tube Ø0.8mm

Pick

FBG Ø125 μm

Flexure

10mm

1mm

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Calibration: Results

- Overall RMS error with 2nd order Bernstein polynomial: 0.67 mN
- Estimation performance in each force direction (total 168 poses)
  - 84.5% (142 poses) < 0.75 mN
  - 96.4% (162 poses) < 1 mN
In-vivo experiments

- Test the force sensing micro-forceps in-vivo using rabbit in the operating room
- Force measurements, stereo microscopic video, and surgeon’s voice annotation were recorded with timestamps for synchronization and analysis

Video overlay of tool tip forces
Use of Audio and Voice

- Voice commands and annotation
- Auditory sensory substitution

![Example Audio Response to Force Input](Image)

**M. Balicki, et al.**
Dual Force Sensor


Follow the Motion of the Eye

**Imaging (OCT) Built Into 0.5mm Surgical Tool**

M. Balicki, J. Han, X. Liu, I. Iordachita, P. Gehlbach, J. Handa, R. Taylor, J. Kang.

- Fourier Domain Common Path OCT (FD CPOCT)
- Combined Superluminescent Diodes
- Functional and structural images

**Autonomous Surface Following**

M. Balicki, J.-H. Han, I. Iordachita, P. Gehlbach, J. Handa, R. H. Taylor, and J. Kang, MICCAI 2010

* 500 µm/s Velocity Limit

Noise Rem. /Threshold/Canny
OCT of Rabbit Retina with Micron-held Probe

X. Liu, M. Balicki, C. Riviere, R. MacLaughlin, et al.

OCT-Guided Motion Control and Compensation with a One Degree-of-Freedom Hand-Held Robot


Two basic functions of the CPOCT-STMC system:
(a) Topological and motion compensation (Safety Barrier),
(b) Targeting and surgical intervention

NIH R01 EY021540
Safety Barrier

Smart Micro-Forceps
M-Scan


M-Scan: *in vivo*

EUS images: E. Boctor
Copyright © 2014 R. H. Taylor

Closed Loop Interventional Medicine

Model → Plan → Evaluation → Action

Patient-specific Evaluation

Information

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

General information
(anatomic atlases, statistics, rules)

Elastography monitoring of ablations

Ex vivo

E-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.

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Reconstruction of injected cement from sparse x-rays


**Example:** Cadaver study with soft tissue and 4 difference images

Closed Loop Interventional Medicine

**Patient-specific loop**

**Process Loop**

**Statistical Analysis**

**Patient-specific Evaluation**

**Model** → **Plan** → **Action**
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.

G. Hager, et al.
The Language of Surgery
Hager, Khudanpur, Vidal + Chen, Lee, Ishii

Data

Models

Assessment

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.

Robots

OR video
The computer-integrated operating room

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

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

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

**Patient Loop** to **Process Loop**
- **Manipulation assistance**
- **Intraoperative information support**
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**Process Loop** to **Patient Loop**
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**The computer-integrated operating room**

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Engineering Research Center for Computer Integrated Surgical Systems and Technology
The computer-integrated operating room

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

The computer-integrated operating room

- Preoperative images & other data
- Intraoperative information support
- Intraoperative analysis
- Manipulation assistance
- Complete record of intervention
- Preoperative images & other data
- Outcome data
- 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/)
Development History

cisst/SAW Software
EEC 9731748, EEC 0646678

Open source mechatronics
MRI 0722943

da Vinci
Research Kit

NRI 1208540
NRI 1327657

SAW Value Proposition

Component Viewer

Python shell

General System Tools

Data collection / replay
User Community

First DVRK User Group Meeting

Johns Hopkins University, March 20-21, 2014
Use Case: Cone-Beam CT-Guided Surgical Navigation

I-STAR Lab

C-arm Setup in the JHU Minimally Invasive Surgical Training and Innovation Center (MISTIC)

Integrated Tracking and Video Augmentation with the Claron MicronTracker

Open-Source Architecture for System Integration

Slide courtesy of J.H. Siewerdsen, Johns Hopkins University

SAW Beyond Surgery

- SAW = Space Assistant Workstation?
- Perform “image-guided surgery” on satellites
  - CT/MRI Image → CAD Model
- Added challenge: time delay (5-10 seconds)
  - Virtual fixtures, semi-autonomous motions, shared control
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