Prediction

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.
What will drive this change?

- New capabilities that **transcend human limitations** in surgery
- Increased **consistency and quality** of surgical treatments
- **Better outcomes** and more **cost-effective** processes in surgical practice

---

**Preoperative**

- Computer-assisted planning
- Patient-specific Model

**Intraoperative**

- Update Model
- Update Plan
- Computer-Assisted Execution

**Postoperative**

- Computer-Assisted Assessment
- Atlas
- Patient
Example: Robotic Joint Replacement Surgery
Example: In-imager Needle Placement

Solomon et al.

Riviere et al.

Webster et al.

Fichtinger et al.

Kennedy et al.

Krieger et al.

Tempany et al.
Example: Augmented Reality in Robot-Assisted Surgical Systems

Clockwise from upper left: daVinci surgical robot; Information overlay of force information on daVinci display (Okamura et al.); Real time overlay of ultrasound images on daVinci display (Taylor et al.)

Information

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

General information (anatomic atlases, statistics, rules)

Closed Loop Medicine

Model → Plan → Action

Patient-specific loop

Patient-specific Evaluation

Process Loop

Statistical Analysis
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**
- Johns Hopkins, MIT, CMU, BWH, Harvard, Penn, Morgan State, Columbia

[cisstweb.cs.jhu.edu]
Closed Loop Medicine

Information

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

General information
(anatomic atlases, statistics, rules)

Closed Loop Medicine

Model → Plan → Action

Patient-specific loop

Patient-specific Evaluation

Process Loop

Statistical Analysis

Information

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

General information
(anatomic atlases, statistics, rules)

Model
Information

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

Model rendering: O. Ahmad

Killian, Pohl, Timoner, ...
Statistical Atlases of Patient Anatomy

Segmentation → Multiple resolution density models → Statistical Analysis → Average model + variation modes

Training Data Sets → Anatomical Labels → Biomechanics → General Surgical Plans → Outcome data → Electronic Anatomical Atlas

Deformable Atlas-to-CT Registration (3D-3D)
Fast simulated x-rays from deforming model

Sadowsky, Taylor, & Cohen
Example: 3D model of patient’s pelvis from three 2D x-ray images and prior statistical atlas.

Example: 3D model of patient’s pelvis from limited field of view x-ray images and atlas.
Example: 2D-3D Reconstruction from 3 DEXA Images+Atlas

**Information**

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

**Model**

- Reconstructed Mesh (Green)
- Reconstructed "CT"
- CT - Reconstruction

**Results**

- Reconstructed QCT
- Actual QCT
- Volume rendering of recon. QCT from DXA

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

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Comparison VXA to QCT

**Model**

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

**General information** (anatomic atlases, statistics, rules)

**Example: Hybrid Cone Beam Reconstruction from Incomplete Projection data & Atlas**

- CT Recon
- Short Scan Recon
- Partial scan Recon
- Atlas-assisted Recon
**Atlas-augmented X-ray Reconstruction**

Taylor, Prince, Yao, Sadowsky, Ramamurthi

**Problem:** Construct dynamically tracked models of deformable surfaces

**Solution:** Optimize a parametric surface from stereo imagery

**Results:** Real-time tracking of a beating heart with:

1. Real-time performance
2. Extremely high accuracy (< 1/10 pixel)
3. Generalization to many imaging devices and applications

**Real-time Video Techniques**

Hager/Thakor/Yuh/Lau (JHU)

**Problem:** Construct dynamically tracked models of deformable surfaces

**Solution:** Optimize a parametric surface from stereo imagery

**Results:** Real-time tracking of a beating heart with:

1. Real-time performance
2. Extremely high accuracy (< 1/10 pixel)
3. Generalization to many imaging devices and applications

Stereo tracking of in-vivo beating heart using Intuitive Stereo Endoscope
Information

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

General information
(anatomic atlases, statistics, rules)

Model → Plan

Example: Integrated environment for image-based planning, visualization, & intervention (SLICER)
Example: Optimal planning of prostate biopsy from US and cancer atlas

D. Shen, C. Davatzikos, Y. Zhan, C. Tempany, G. Fichtinger, S. Haker, ...

Example: Biomechanical Simulation of Medical Needle Insertion
Ron Alterovitz, Ken Goldberg (UC Berkeley)
Jean Pouliot, I-Chow Hsu (UCSF)

• **Goal:** Reduce radioactive seed placement error in prostate cancer brachytherapy treatment using biomechanical simulation
• Developed 2D dynamic finite element model of needle insertion in tissue
• Interactive simulation: 24 fps on a 750MHz PC
• **Applications:** Physician training and treatment planning

Tissue deformations cause seed placement error
Planner computes offsets to compensate for simulated tissue deformations
Example: Planning Access and Safety Constraints for Skull Base Drilling

P. Kazanzides, C. Baird, T. Xia, N. Hata, …
Information

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

General information
(anatomic atlases, statistics, rules)

Example: Robotic Knee Replacement Surgery

Model → Plan → Action

Example: Surgical Navigation Systems

Model → Plan → Action
Model
Plan
Action

Example: Robotically-assisted needle placement

Information

Courtesy: Integrated Surgical Systems
Robotic Needle Guidance

Information

Patient-specific information (images, lab results, genetics, etc.)

Example: Computer-integrated prostate brachytherapy

Model → Plan → Action

Kennedy, Fichtinger, Burdette, et al.
**X-ray-guidance example:**
Percutaneous access to kidney
- Radiolucent needle driver
- Robot aligns needle under x-ray fluoroscopy guidance
- Has been done both locally and remotely

Photos: D. Stoianovici, L. Kavoussi

**RCM Robot with Radiolucent Needle Driver**

Stoianovici, Taylor, Whictomb, et al.
Model

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

General information (anatomic atlases, statistics, rules)

Information

Plan

Action

Example: CT-guided robot for biopsy and therapy

Example: MRI-guided robot for trans-rectal prostate biopsy and therapy

CREDIT: Krieger, Susil, Ménard, Coleman, Singh, Whitcomb, Atalar, Fichtinger

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Engineering Research Center for Computer Integrated Surgical Systems and Technology
Example: MRI-guided robot trans-perineal prostate brachytherapy

D. Stoainovici, A. Patriciu, et al.

Steering the needle ...
Information

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

Example: Image overlay system for in-scanner needle placement

Model → Plan → Action

Robotic Needle Placement in Rodents

P. Kazanzides, G. Fichtinger, C. Ling

Credit: Jack Li, I. Iordachita

Micro-PET scanner

Research contract from Sloan Kettering

Courtesy of MSKCC
Small Animal Radiation Research Platform
John Wong (PI), Peter Kazanzides, et al.

- Prototype, self-contained, very compact imaging and radiation therapy research platform for small animals
- In development as collaboration between JHU Radiation Oncology and CISST ERC

---

Information

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

General information (anatomic atlases, statistics, rules)

Surgical Assistant Workstation

Patient-specific loop

Statistical Analysis
Kidney Ischemia Assessment

- Major concern in laparoscopic partial nephrectomies
- Preliminary *in vivo* study on pigs using fiber-optic probe and visible light spectroscopy

Sabrina Shen, Yi Yang, Marcin Balicki, Lia Assumpcao, Michael Marohn, David Hernandez, Li-Ming Su, Russell Taylor
Kidney Ischemia Assessment

Sabrina Shen, Yi Yang, Marcin Balicki, Lia Assumpcao, Michael Marohn, David Hernandez, Li-Ming Su, Russell Taylor

Abs Signal During Ischemia

Abs Amplitude

Time (min)

Unclamp

Example: Telesurgical Assistants

Information

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

General information (anatomic atlases, statistics, rules)

Model

Plan

Action

Photo: Intuitive Surgical
Research Applications and Subsystems

- Haptics
- Task modeling
- Skill Assessment
- Remote telesurgery
- Etc.

• Stereo processing
• Tool tracking
• Image registration
• Interactive visualization
• Ultrasound

Example: Overlay of CT model onto laparoscopic video in kidney tumor resection

Information

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

Model

Plan

Action

Example: Intraoperative Laparoscopic Ultrasound with daVinci

Example: Snake-like robot for minimally invasive surgery of the throat and upper airway

Example: Snake-like robot for minimally invasive surgery of the throat and upper airway

Example: CMU HeartLander Robot for Epicardiac Procedures

Patient-specific Information (Images, lab results, genetics, etc.)
Example: Microsurgery Tremor Reduction

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

CMU MICRON Robot
Ang, Machiachian, Riviere

JHU Steady Hand “Eye Robot”
Iordachita, Kapoor, Kazanzides, Taylor

Example: Steady-hand robot for microsurgery

Taylor, Iordachita, Kapoor, Handa, Mitchell, Fleming, Gehlbach et al.
Example: Steady-hand guiding and virtual fixtures for single-cell injections

Model → Plan → Action

Our Experimental Setup

Holding Section
Camera

Lecia Inverted Microscope

Injection Section
“Steady Hand” Robot

Micrometer Drive
Injection step strategies

- **Compliant**
  - The robot complies with scaled user forces
- "Augmented" compliant
  - Asymmetric and non-linear compliance gains
  - Slow approach
  - Faster withdrawal to facilitate sealing
  - Selective locking of DOF
- **Supervisory**
  - User selects injection point and robot injects

Results

Completion times for different strategies

<table>
<thead>
<tr>
<th></th>
<th># Trials</th>
<th>Time Required (seconds)</th>
<th>Survival Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Average</td>
<td>Std. Dev</td>
</tr>
<tr>
<td><strong>Approach</strong></td>
<td>20</td>
<td>109.8</td>
<td>78.5</td>
</tr>
<tr>
<td><strong>Injection/ Withdraw</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compliant</td>
<td>2</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td>Augmented</td>
<td>8</td>
<td>0.747</td>
<td>0.067</td>
</tr>
<tr>
<td>Supervisory</td>
<td>12</td>
<td>0.678</td>
<td>0.024</td>
</tr>
</tbody>
</table>

- These results are from single user trials, not trained in conventional setup
- These times are indicative of speed of microinjection and are preliminary
Evolution to human-machine partnership

• Situation assessment
• Task strategy & decisions
• Sensory-motor coordination

Augmentation System
• Sensor processing
• Model interpretation
• Display
• Online references & decision support
• Manipulation enhancement
• Cooperative control and "macros"

atlases
libraries

R. Taylor
Evolution to human-machine partnership

- Situation assessment
- Task strategy & decisions
- Sensory-motor coordination

Augmentation System
- Sensor processing
- Model interpretation
- Display
- Online references & decision support
- Manipulation enhancement
- Cooperative control and "macros"

Enhanced Interfaces for Surgical Robots

IBM/JHU LARS, circa 1993-4
Dynamic Augmented Reality for Sensory Substitution in Robot-Assisted Surgical Systems

Sensory substitution of force information improves performance:

<table>
<thead>
<tr>
<th>Metric</th>
<th>p-value</th>
<th>Significant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of broken sutures</td>
<td>.0111</td>
<td>Y</td>
</tr>
<tr>
<td>Standard deviation of forces</td>
<td>.0414</td>
<td>Y</td>
</tr>
<tr>
<td>Average peak applied force</td>
<td>.0539</td>
<td>*</td>
</tr>
<tr>
<td>Number of loose knots</td>
<td>.0667</td>
<td>*</td>
</tr>
<tr>
<td>Average task completion time</td>
<td>.7934</td>
<td>N</td>
</tr>
</tbody>
</table>

Example: “Virtual fixtures” for safety and surgical assistance

Information

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

General information (anatomic atlases, statistics, rules)
Constrained Optimization Framework

• Single frame
  \[ \begin{bmatrix} H_p \\ H_r \end{bmatrix} J(q) \Delta q \geq \begin{bmatrix} h_p \\ h_r \end{bmatrix} \]

• Multiple frames
  \[ \begin{bmatrix} H_I \\ 0 \\ \cdots \\ 0 \\ H_k \end{bmatrix} \begin{bmatrix} J_I(q) \\ \vdots \\ \vdots \\ J_k(q) \end{bmatrix} \Delta q \geq \begin{bmatrix} h_I \\ \vdots \\ \vdots \\ h_k \end{bmatrix} \]

Select one or more

Customized virtual fixtures

Steady-hand sinus surgery with virtual fixtures derived from CT models
Ming Li, Russell Taylor

tip point path
bent tip portion
tool shaft portion
Virtual Fixture Online Implementation

- Registered model
- Path
- Tool tip guidance
- Virtual fixture
- Constraint generation
- State
- Robot interface

\[
\begin{align*}
\text{min} & \left\| W \cdot (J_{tip} \cdot \Delta q - \Delta P_{des}) \right\|^2 \\
\text{Subject to} & \quad G \cdot \Delta q \geq g
\end{align*}
\]

Registered model: M. Li; R. Taylor; ICRA 2005
Cooperative control guiding: 3D mouse guiding
View of path & tool: M. Li; R. Taylor; ICRA 2005
Performance of Teleoperation vs Cooperatively Hands-on Operation

Trajectory of the path

Yellow: given path; Red: remote; Blue: hands-on

Robot context  Optical Tracking context

Information

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

General information
(anatomic atlases, statistics, rules)

Example: “Virtual fixtures” for suturing assistance

<table>
<thead>
<tr>
<th></th>
<th>Entry</th>
<th>Exit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Robot VF</td>
<td>0.63 ± 0.12</td>
<td>0.77 ± 0.37</td>
</tr>
<tr>
<td>Manual</td>
<td>--</td>
<td>2.1 ± 1.2</td>
</tr>
</tbody>
</table>
Information

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

General information
(anatomic atlases, statistics, rules)

Example: “Virtual fixtures” for suturing assistance

Model → Plan → Action

Example: Two-handed virtual fixture for centering knot with visual feedback

Model → Plan → Action

Ankur Kapoor
Example: Steady-hand guiding and virtual fixtures for neurosurgery

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

General information (anatomic atlases, statistics, etc.)

Kazanzides, Tian, Baird, Jallo
Research Issue: Understanding intent in human-machine cooperation

Information

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

General information (anatomic atlases, statistics, rules)

Model → Plan → Action
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

---

Information

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

General information (anatomic atlases, statistics, rules)

Model  Plan  Action

Evaluation

Patient-specific Evaluation
Example: Intraoperative Assessment of Brachytherapy Patterns

Patient-specific Information

- Model
- Plan
- Action

Patient-specific Evaluation

Example: Jain et al. Intraoperative Assessment of Brachytherapy Patterns

US-Guided Ablation of Tumors

Targeting & Assessment – US Probe Placement – Freehand or robot Monitoring

Emad Boctor, G. Fichtinger, M. Awad, M. deOliveira, R. Ghanem, R. Taylor, M. Choti
Model

Plan

Action

Patient-specific Evaluation

Statistical Analysis

Process Loop

Closed Loop Medicine

Example: Ultrasound strain imaging to monitor thermal ablation of liver tumors

Patient-specific Evaluation

Information

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

General information (anatomic atlases, statistics, rules)

Emad Boctor, G. Fichtinger, M. Awad, M. deOliveira, R. Ghanem, R. Taylor, M. Choti

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Engineering Research Center for Computer Integrated Surgical Systems and Technology
Example: Adaptive Radiation Therapy

Information

- Patient-specific information (images, lab results, genetics, etc.)
- General information (anatomic atlases, statistics, rules)

Statistical Analysis

Information-Intensive Interventional Suite

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

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

- Assistant Workstation

- Surgeon Interfaces

- Anesthesia, vital signs, logistics, back table, etc.
- Robots
- OR video
Ensuring no sponge (or instrument) gets left in the patient

Lia Assumpcao, Michael Marohn, Rosemary Mountain, Nilo Rivera, Russell Taylor, and Allen A. Williams

Evolution: Integrating Imaging, Intervention, and Informatics in Medicine (I^4 M)

**Strategy:** develop comprehensive program to address the technological, clinical and educational challenges that need to be met in order to fundamentally transform interventional medicine in the same ways that computer-integrated systems have transformed manufacturing and other sectors of our society.

- Transcend human limitations.
- Improve safety, consistency, and overall quality.
- Improve the efficiency and cost-effectiveness.
- “Closed loop medicine”
  - For treating individual patients
  - Improving treatment processes
Integrating Imaging, Intervention, and Informatics in Medicine (I^4M)

Technology & Systems
- Imaging & analysis
- Robotics & devices
- Systems
- Clinical engineering
- Validation, quality control, safety
- Informatics

Clinical Applications
- Microsurgery
- MIS
- Image-guided local interventions
- Targeted energy delivery
- etc.

Education & Infrastructure
- Laboratories
- Training facilities
- Simulation
- Certification
- Traineeships
- Fellowships
- Seminars
- Outreach
- Formal Courses

New Home for ERC Engineering Activity at JHU

Laboratory for Computational Sensing and Robotics (LCSR)
- Approx 15,000 square feet in new building on engineering campus
- Main shared lab area
- 10 adjoining labs
- Mock operating room
- Offices for faculty, staff, post-docs, students
- Come see us!
How can we get there?

Strong and committed teams
- Surgeons
- Engineers
- Industry

Focus on systems that address important needs

Rapid iteration with measurable goals

Have fun!

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