Computer-Integrated Interventional Medicine: Integrating Imaging, Intervention, and Informatics to Improve Patient Care

Russell H. Taylor
Professor of Computer Science, with joint appointments in Mechanical Engineering, Radiology & Surgery
The Johns Hopkins University
mtl@jhu.edu

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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

Example: Robotic Joint Replacement Surgery

Surgical "CAD"  Surgical "CAM"  Surgical "TQM"
**Information**

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

General information (anatomic atlases, statistics, rules)

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**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

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**Example: Surgical Navigation Systems**

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**Example: Optimal planning of prostate biopsy from US and cancer atlas**

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**Navigation Systems**

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Information

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General information
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Model ➔ Plan ➔ Action

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

Information

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- Images, lab results, genetics, etc.

General information
- Anatomic atlases, statistics, rules

Model ➔ Plan ➔ Action

Example: MRI-guided robot trans-perineal prostate brachytherapy

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Model ➔ Plan ➔ Action

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

RCM Robot with Radiolucent Needle Driver

Information

Patient-specific information
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- Anatomic atlases, statistics, rules

Model ➔ Plan ➔ Action

Example: CT-guided robot for biopsy and therapy
**Robotic “Third Hand” Assistants**

- Limb positioners
- Retractors
- Endoscope holders
  - *Aesop*
  - IBM/JHU LARS
  - etc.
- Can incorporate sophisticated HMI, voice, vision, etc.

**Telerobotic Surgical Augmentation**

SRI telesurgery system, circa 1992

**Human-machine cooperative manipulation in surgery**

Situation assessment
Task strategy & decisions
Sensory-motor coordination

Display
Sensors
- Online references & decision support
- Manipulation enhancement
- Cooperative control & “macros”

**Information**

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

**Example: CMU “HeartLander” robot for crawling across the heart**

**Information**

Patient-specific information
- Images, lab results, genetics, etc.

General information
- Anatomic atlases, statistics, rules
Evolution to human-machine partnership

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

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

Vagvolgyi, Hager, et al.

Dynamic Augmented Reality for Sensory Substitution in Robot-Assisted Surgical Systems

Sensory substitution of force information improves performance:

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Real Time Deformable Registration and Overlay

Final registration error of < 1mm except for the area where the tool enters the image
**Model-Patient-specific Information**

- **Images, lab results, genetics, etc.**

**General Information**
- (anatomic atlases, statistics, rules)

**Example: “Virtual fixtures” for safety and surgical assistance**

1. **Model**
2. **Plan**
3. **Action**

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**Virtual Fixture Online Implementation**

- **Path**
- **Tool tip guidance virtual fixture**
- **Robot interface**

**State**

- 

\[
\min_W \left\{ \sum_{i=0}^{n} (\Delta q_i) \left( \sum_{j=0}^{m} (\Delta P_j) \right) \right\}
\]

Subject to

\[
G \cdot \Delta q \geq g
\]

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**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**

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**Steady-hand sinus surgery with virtual fixtures derived from CT models**

**Ming Li, Russell Taylor**

- **tip point path**
- **bent tip portion**
- **tool shaft portion**

**Cooperative control guiding**

**3D mouse guiding**

**View of path & tool**

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**Example: Steady-hand guiding and virtual fixtures for neurosurgery**

- **Model**
- **Plan**
- **Action**

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**Information**

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

- **General information** (anatomic atlases, statistics, rules)
External Beam Radiotherapy

**PLANNING** (once)  **TREATMENT** (x40)

Planning CT  
\[65,000 \text{ patients} \] 
\[2.6 \text{ million treatments} \]

aSi portal image

**Problem: Dancing Prostate**

Inter-fractional Motion from Serial CT – Movement AP \(\pm 1\text{cm}^2\)

Credit: Andrew Zimmerman, MD, (MGH)

US Based Prostate Localization?

- Poor image quality
- Operator dependent
- Prostate sources

CREDIT: Resonant, REGISTER platform

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

Example: Adaptive Radiation Therapy

Patient-specific Evaluation

Statistical Analysis
Strategy for evolution at JHU

- Joint venture of medical & engineering schools with medical school as senior partner
- Strong presence on both campuses
- Home for engineers, permanent staff
- Education & training initiatives
- Outreach & with other institutions

Evolution: Integrating Imaging, Intervention, and Informatics in Medicine (IM)

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 way 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

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

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!
What research is really like

Discussion

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