NSF Engineering Research Center
for Computer Integrated Surgical
Systems and Technology

Computer-Integrated Interventional Medicine:

Integrating Imaging, Intervention, and Informatics to Improve Patient Care

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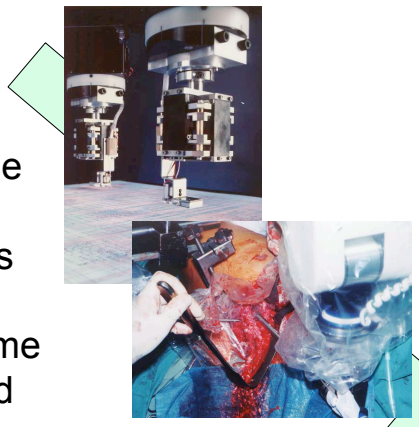
WHITING SCHOOL OF ENGINEERING
THE JOHNS HOPKINS UNIVERSITY

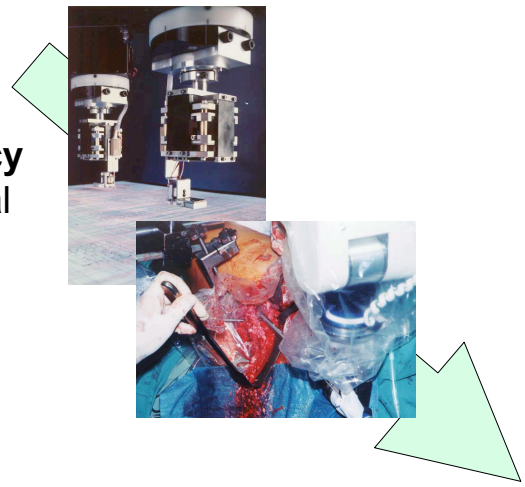
Prediction

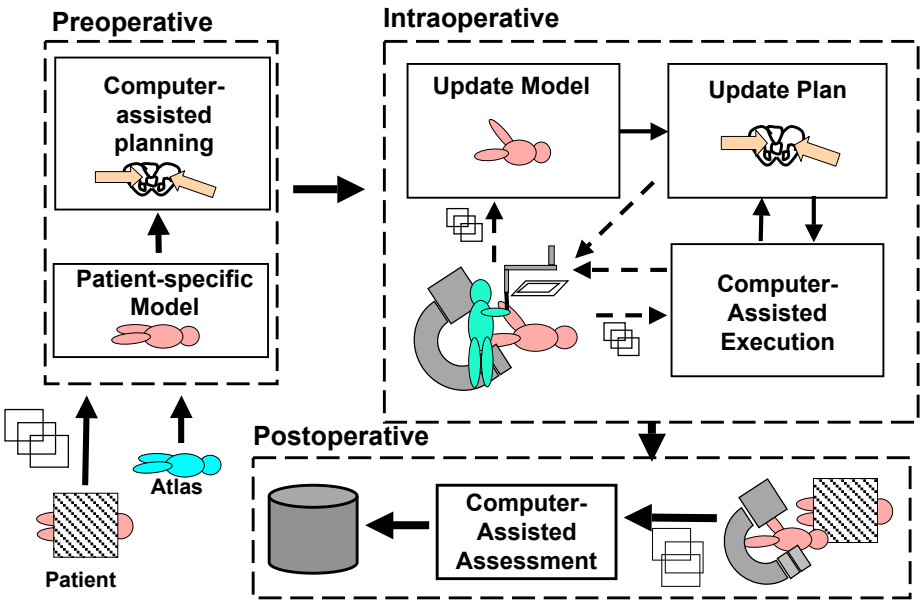
A partnership between human clinicians and computer-based technology will fundamentally change the way surgery and interventional medicine is performed in the 21st Century, in much the same way that computer-based technology changed manufacturing in the 20th Century

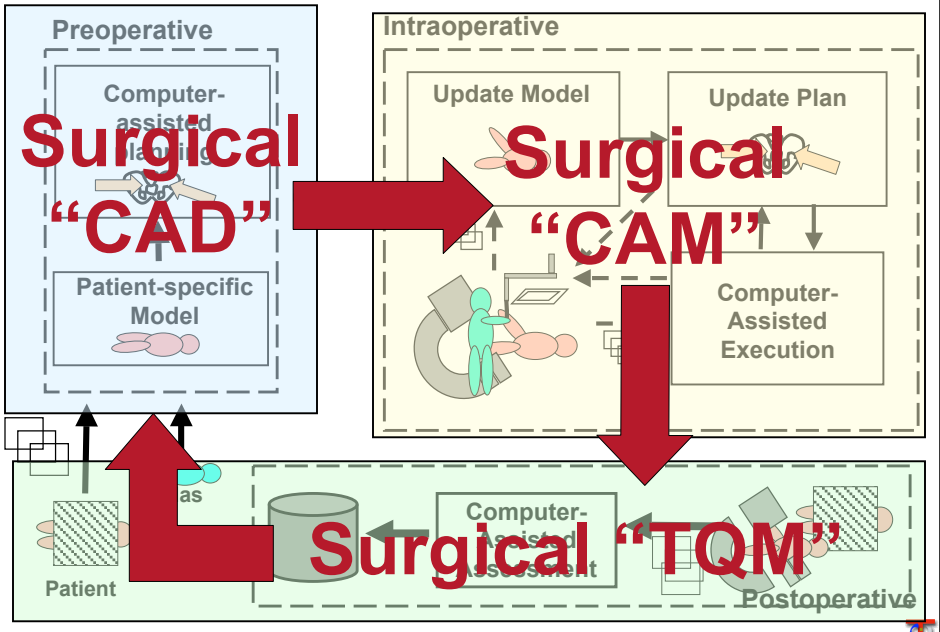


What will drive this change?

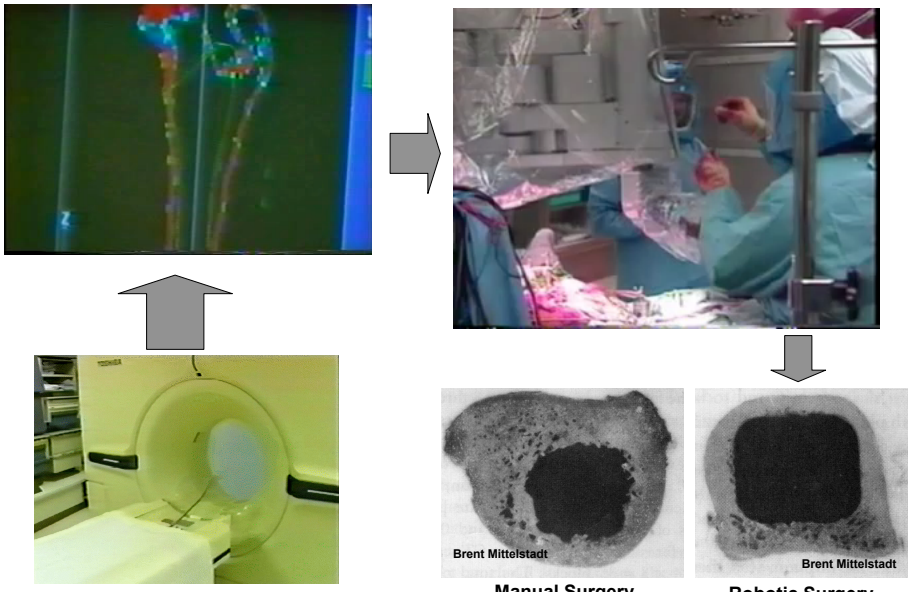
- New capabilities that **transcend human limitations** in surgery
- Increased **consistency and quality** of surgical treatments
- **Better outcomes** and more **cost-effective** processes in surgical practice







Example: Robotic Joint Replacement Surgery



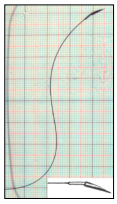
Taylor, Kazanzides, Paul, Mittelstadt, *et al*.

Manual Surgery

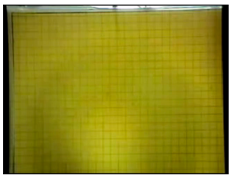
Robotic Surgery

Example: In-imager Needle Placement

Solomon *et al.*

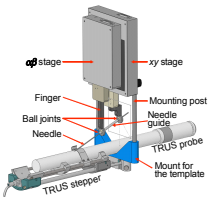


Riviere *et al.*

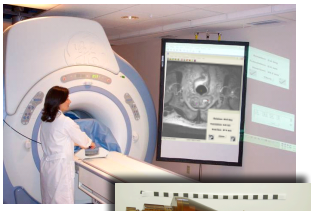


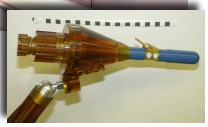
Webster *et al.*

Fichtinger *et al.*

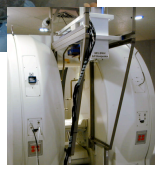


Kennedy *et al.*

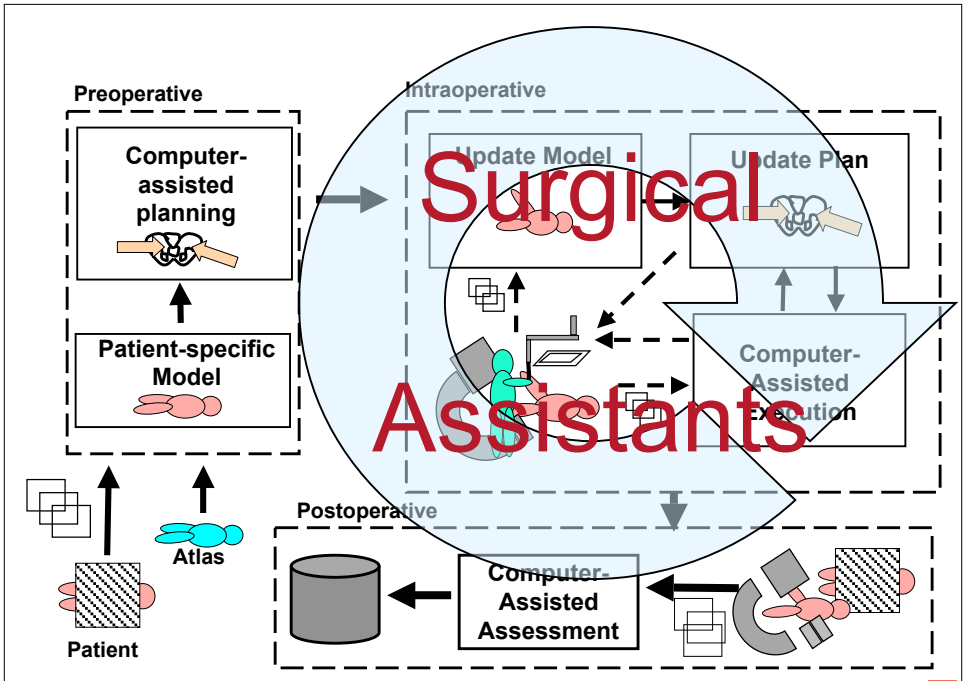




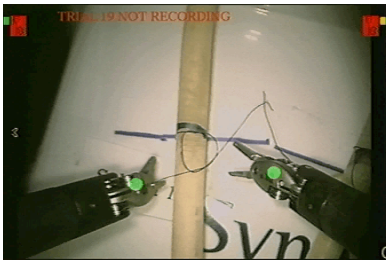
Krieger *et al.*

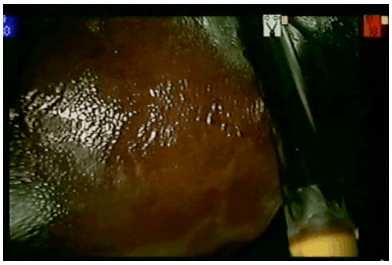


Tempany *et al.*



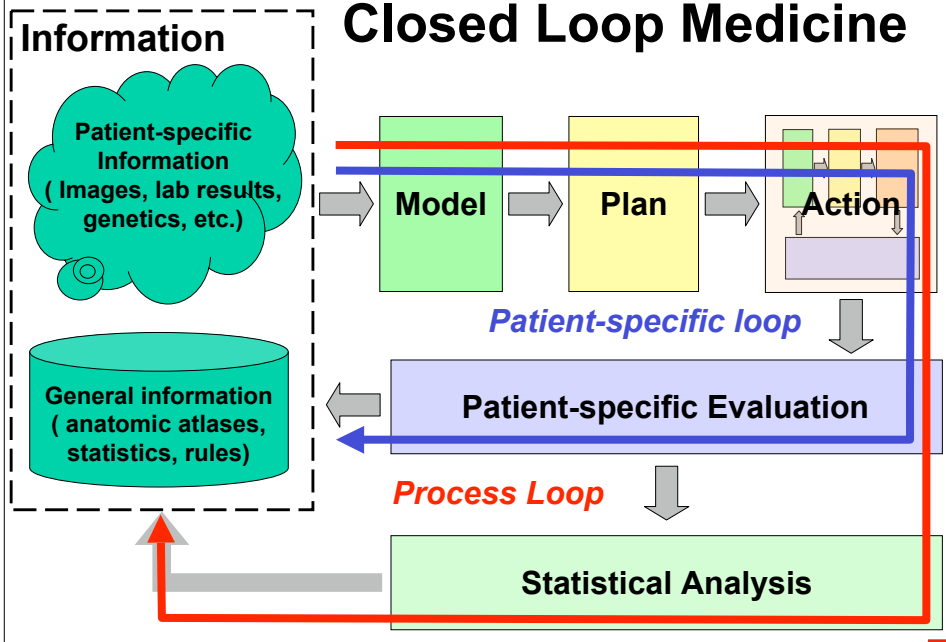
Example: Augmented Reality in Robot-Assisted Surgical Systems





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.*)

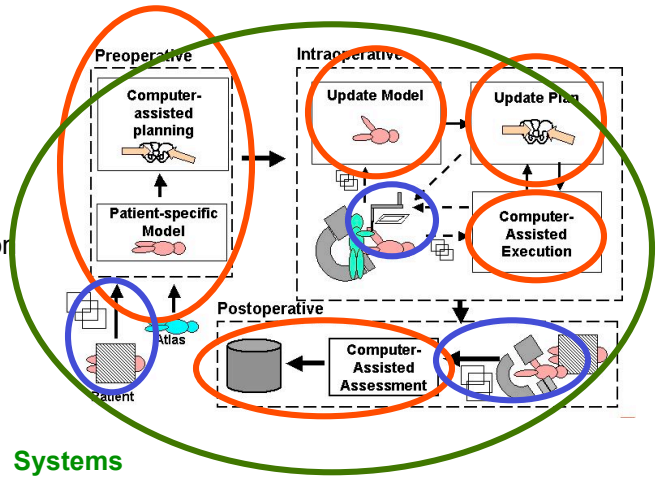
Closed Loop Medicine



Multidisciplinary Integration is Crucial

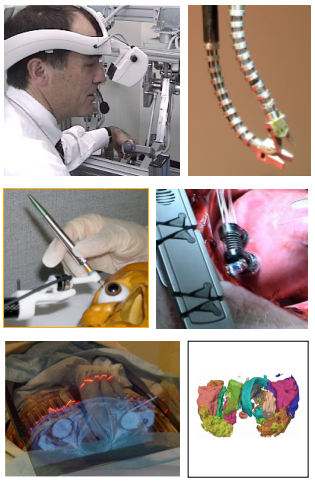
Modeling & analysis
- Segmentation
- Registration
- Atlases
- Optimization
- Visualization
- Task characterization
- *etc.*

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)



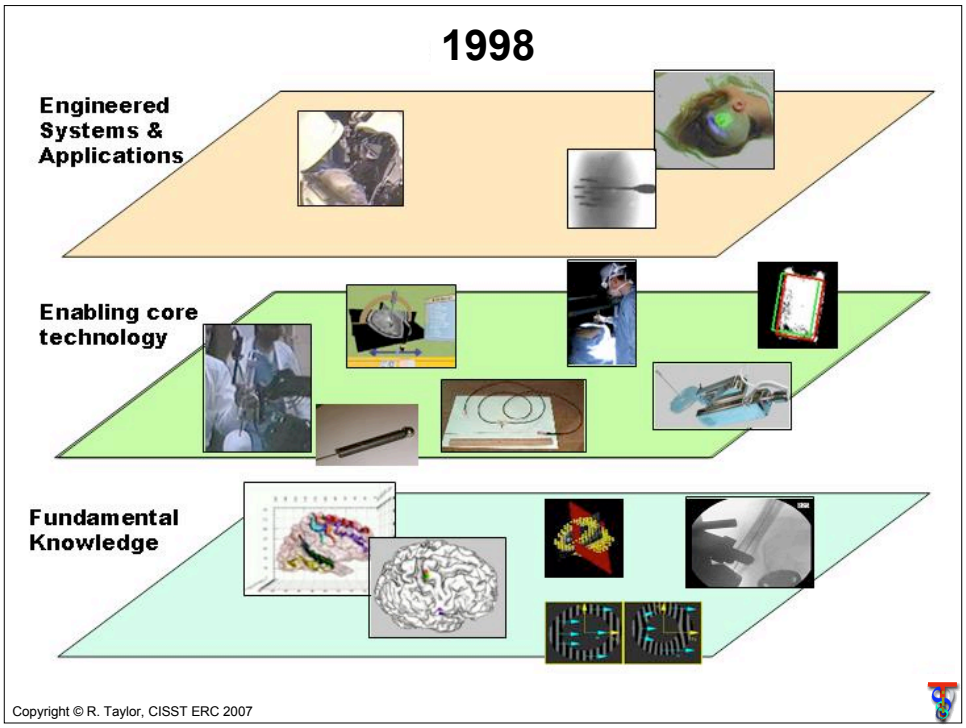
cisstweb.cs.jhu.edu

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, Georgetown, …

Funding
- Year 9: Core NSF Grant = $2.7M; Total = $6.8M
- Year 10: Core NSF Grant =$1.8M; Total =$8.2M
- Years 1-10: Core NSF Grant = $30.2M; Total = ~$62M


1998
Engineered Systems & Applications
Enabling core technology
Fundamental Knowledge
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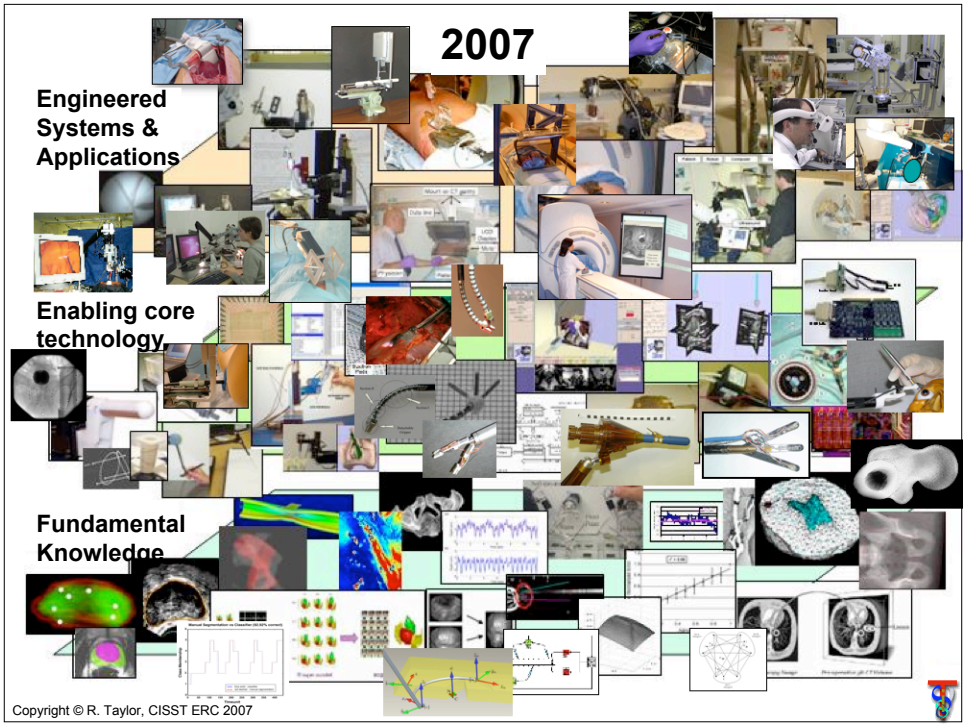
2007
Engineered Systems & Applications
Enabling core technology
Fundamental Knowledge
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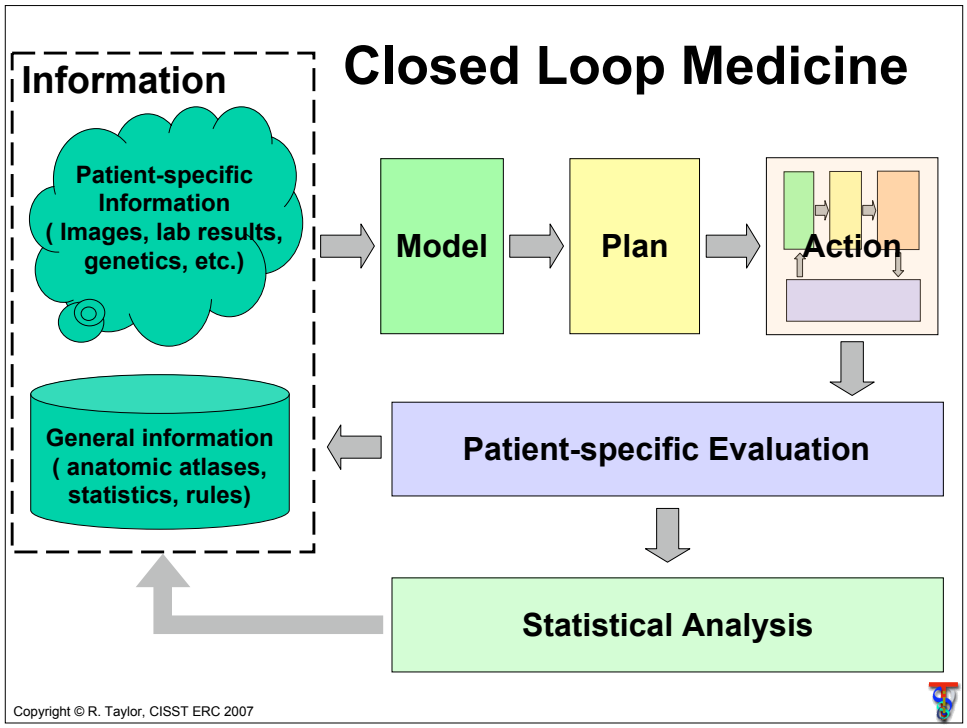
Closed Loop Medicine
Information
Patient-specific Information (Images, lab results, genetics, etc.)
General information (anatomic atlases, statistics, rules)
Model
Plan
Action
Patient-specific Evaluation
Statistical Analysis
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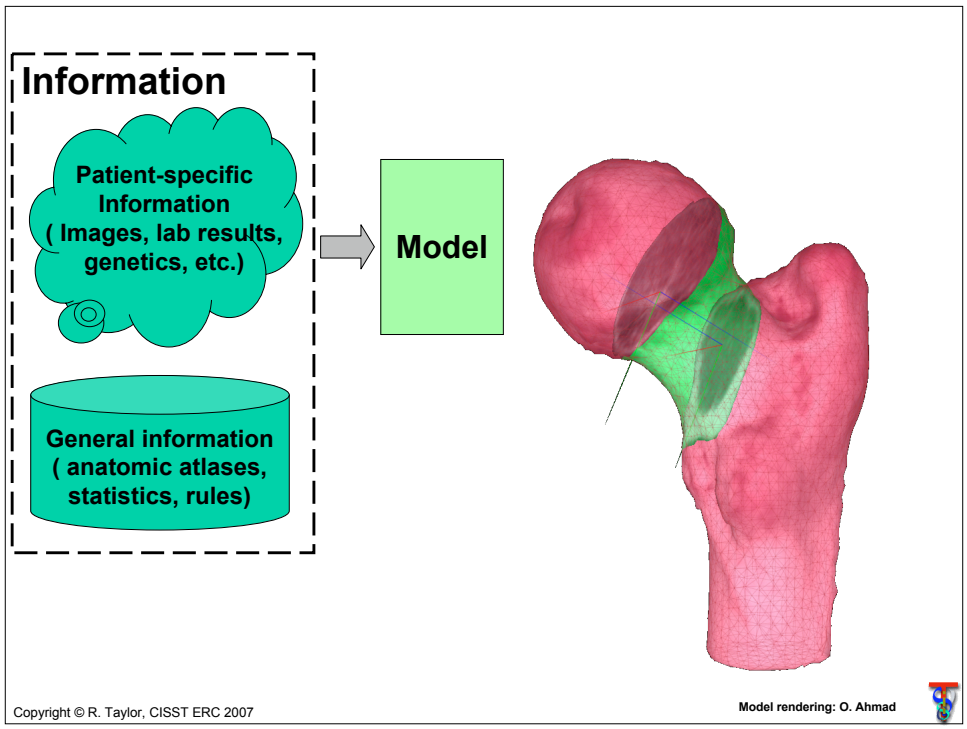
Information
Patient-specific Information (Images, lab results, genetics, etc.)
General information (anatomic atlases, statistics, rules)
Model
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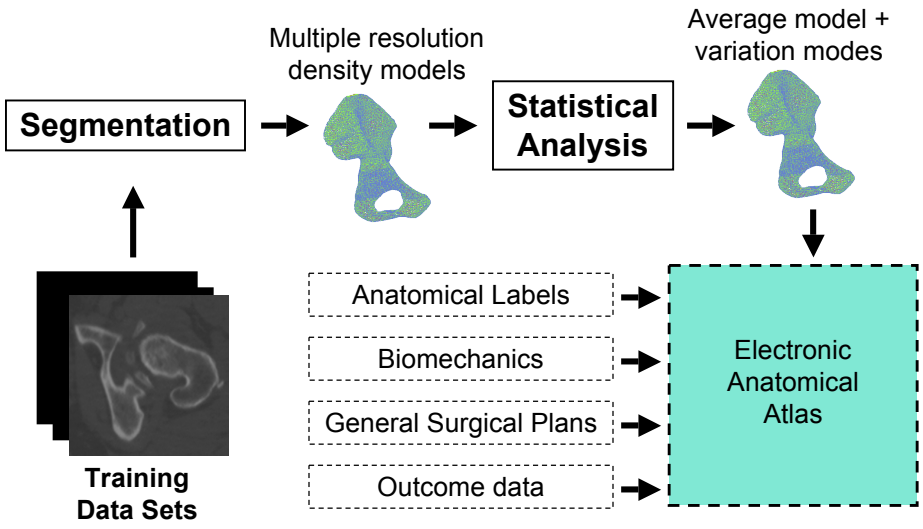
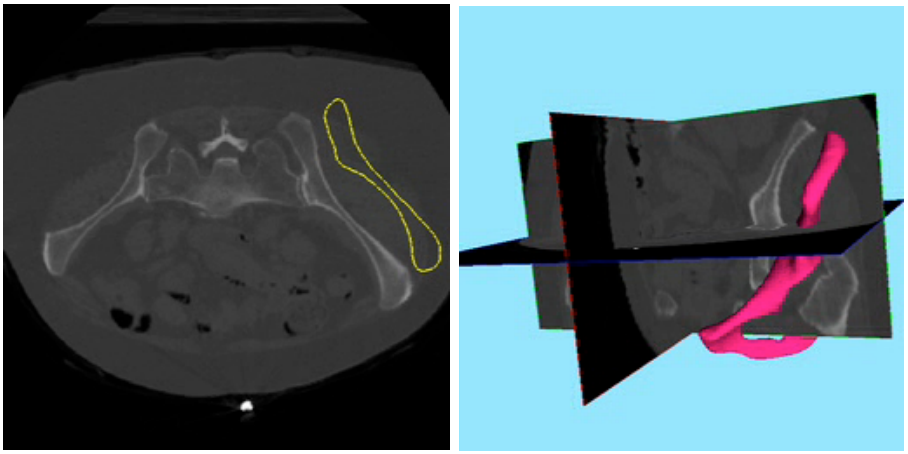
Model rendering: O. Ahmad

Statistical Atlases of Patient Anatomy

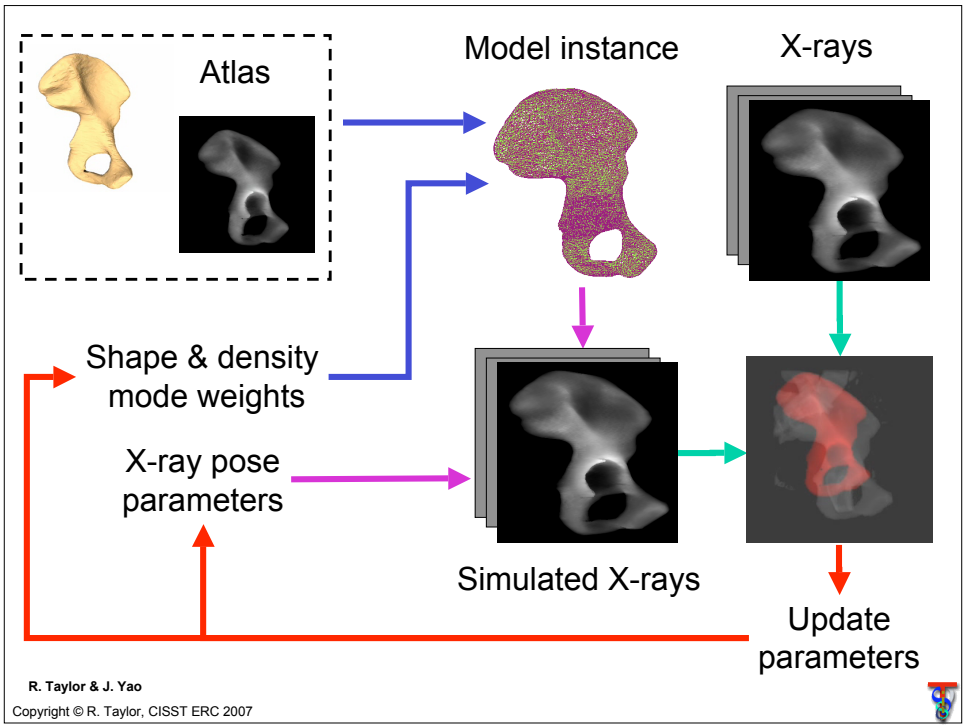


R. Taylor & J. Yao

Deformable Atlas-to-CT Registration (3D-3D)



Jianhua Yao


Atlas
Model instance
X-rays
Shape & density
mode weights
X-ray pose
parameters
Simulated X-rays
Update
parameters
R. Taylor & J. Yao
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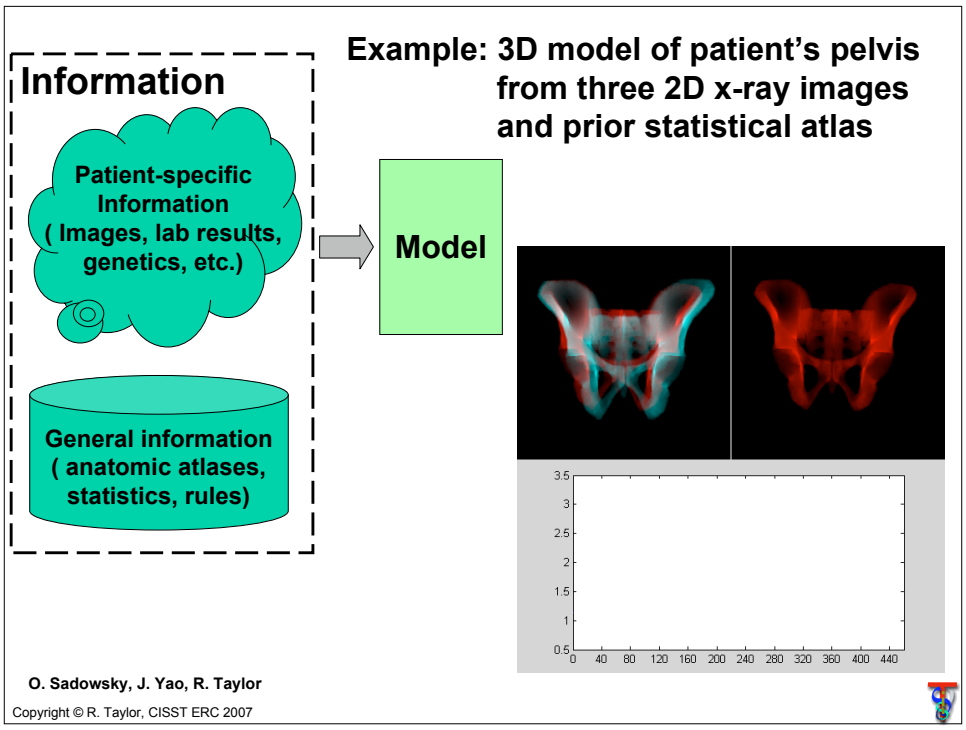
Example: 3D model of patient's pelvis
from three 2D x-ray images
and prior statistical atlas
Information
Patient-specific
Information
(Images, lab results,
genetics, etc.)
General information
(anatomic atlases,
statistics, rules)
Model
3.5
3
2.5
2
1.5
1
0.5
0
40
80
120
160
200
240
280
320
360
400
440
O. Sadowsky, J. Yao, R. Taylor
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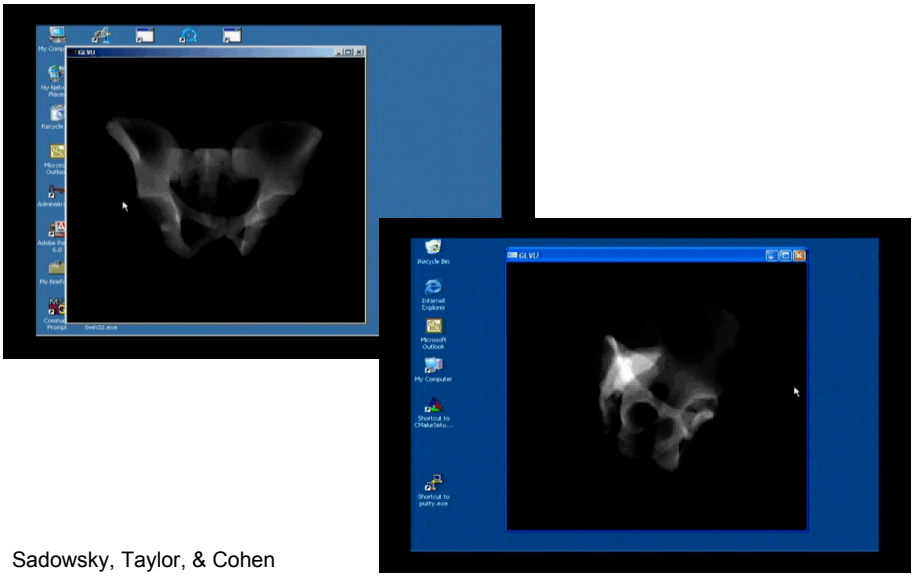
Fast simulated x-rays from deforming model

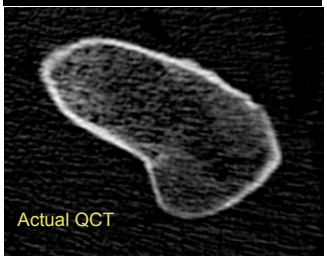


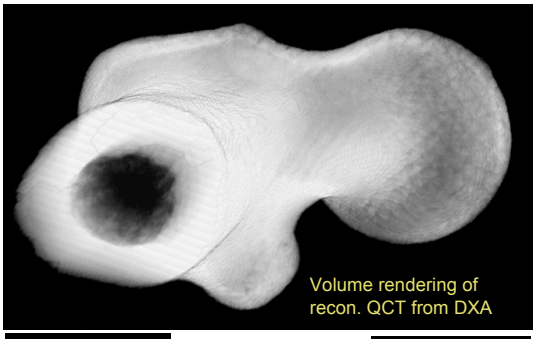
Sadowsky, Taylor, & Cohen

Example: 2D-3D Reconstruction from 3 DEXA Images+Atlas

JHU: Omar Ahmad, 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

Results

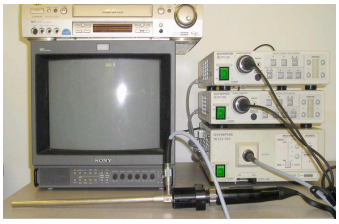


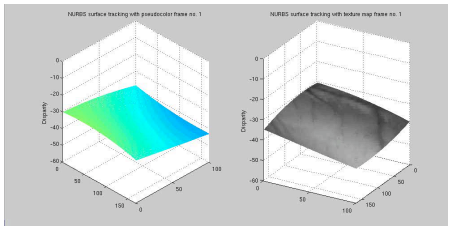


JHU: Omar Ahmad, Ofri Sadowsky, Russell Taylor
U. Erlangen: Klaus Engelke
BIDMC, Boston: Mary Bouxsein
Inst. of Aging Research, Boston: David Karasik
Hologic, Inc.: Krishna Ramamurthi, Kevin Wilson

Real-time Video Techniques

Hager/Thakor/Yuh/Lau (JHU)



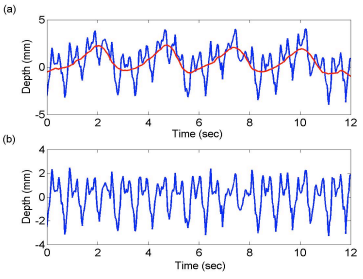


Problem: Construct dynamically tracked models of deformable surfaces

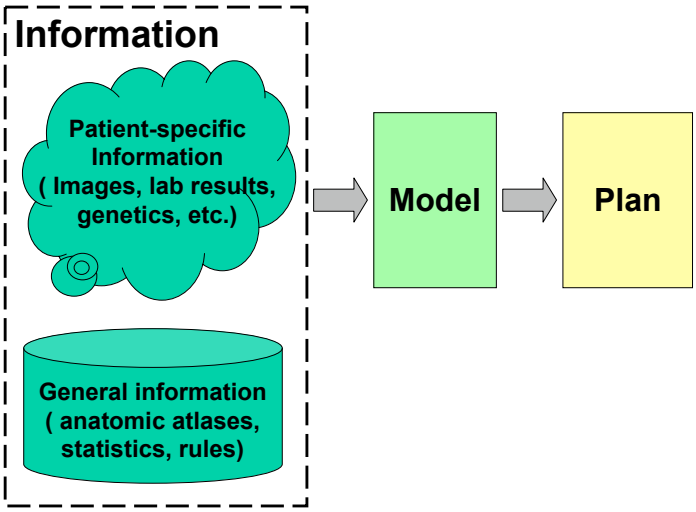
Solution: Optimize a parametric surface from stereo imagery

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

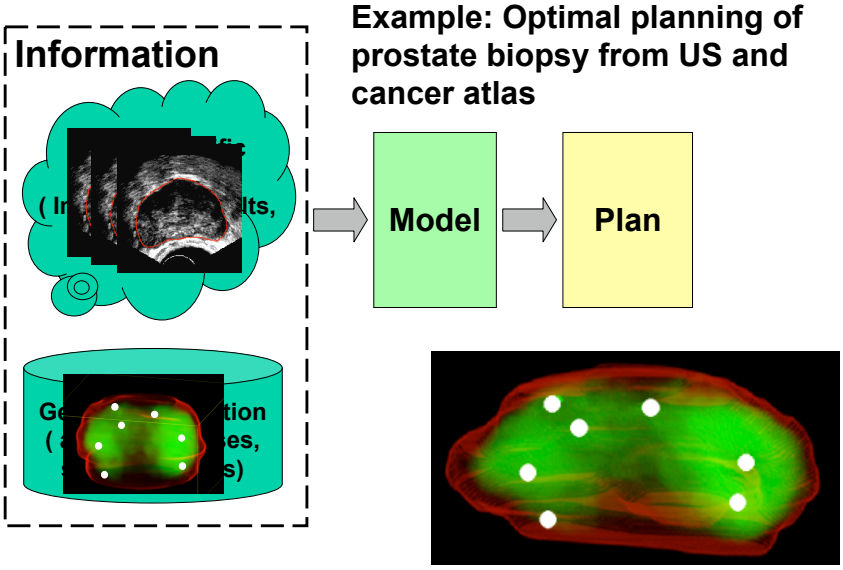
1. Real-time performance
2. Extremely high accuracy (< 1/10 pixel)
3. Generalization to many imaging devices and applications



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



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

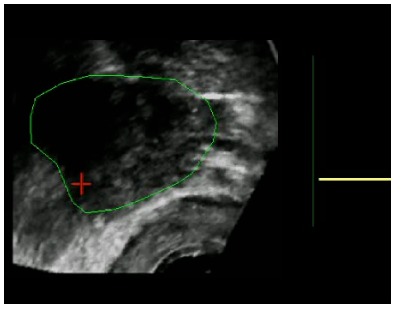


D. Shen, C. Davatzikos, Y. Zhan, C. Tempany, G. Fichtinger, S. Haker, …

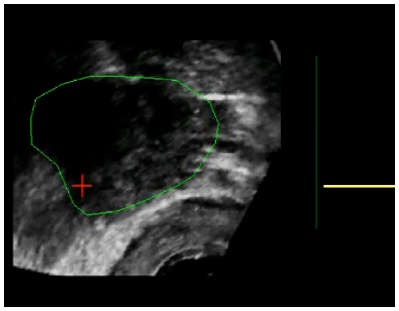
Example: Biomechanical Simulation of Medical Needle Insertion

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

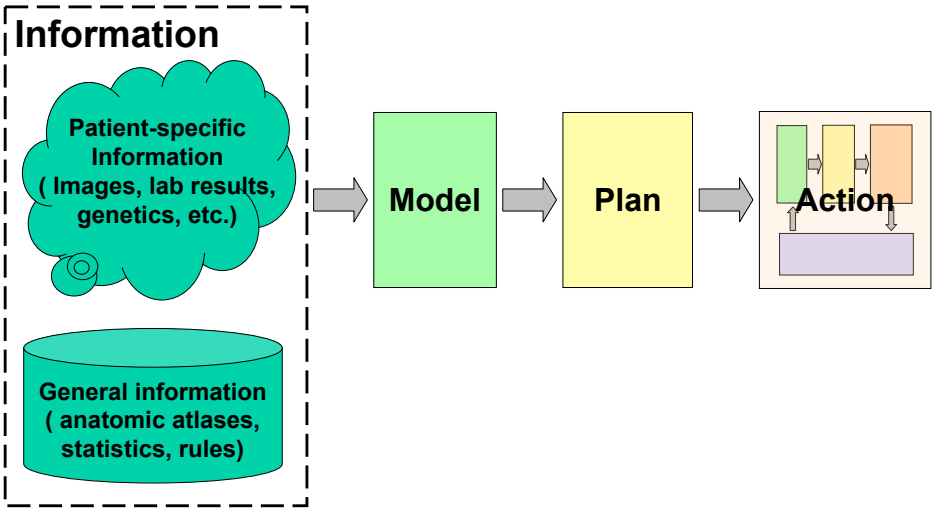
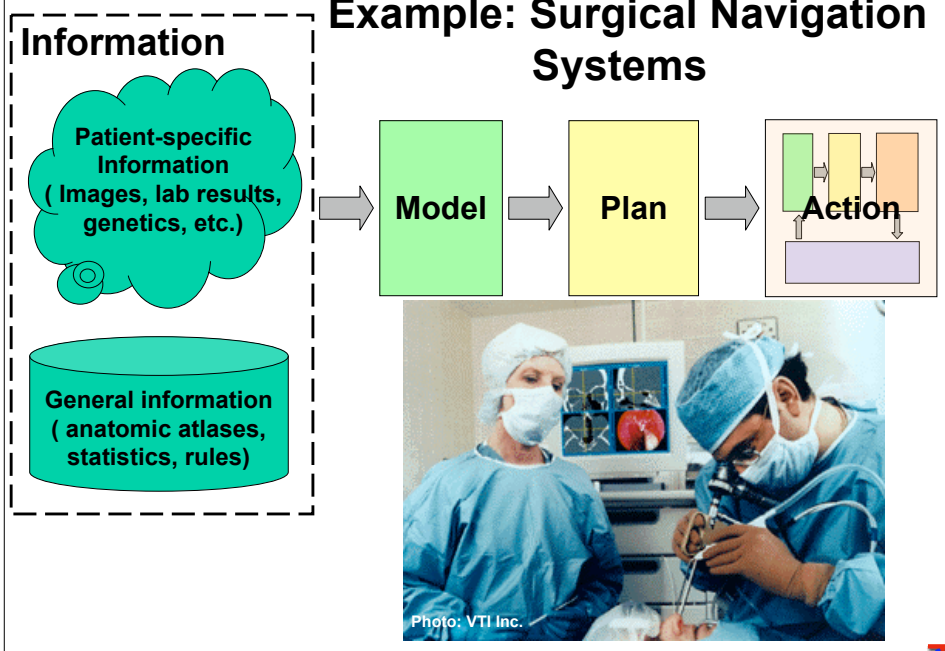
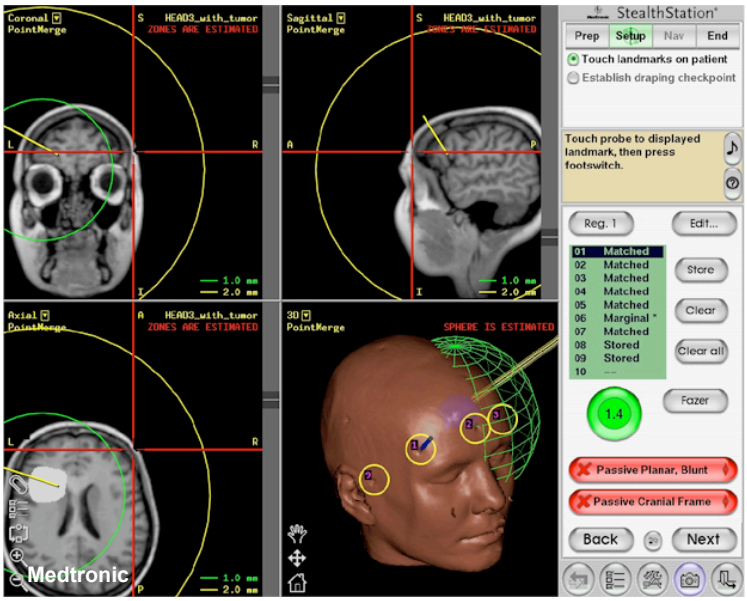


Figure: R. Taylor

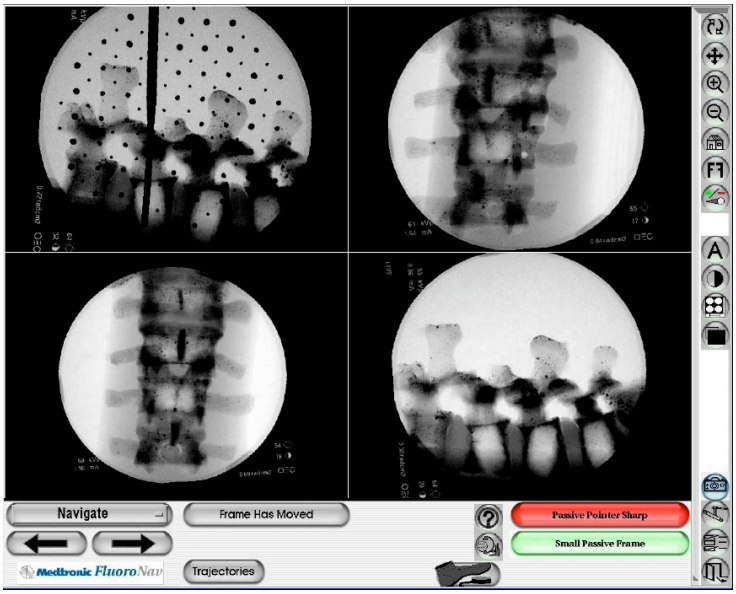
Example: Surgical Navigation Systems

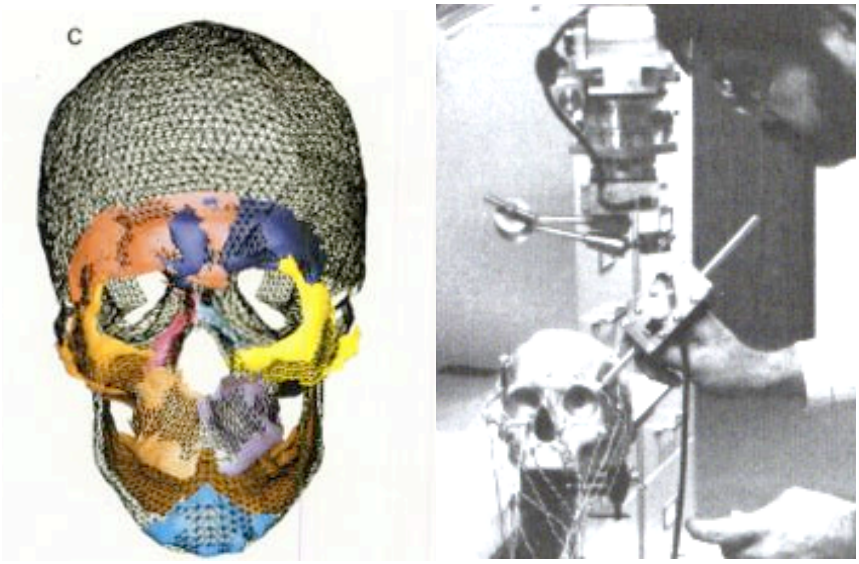


Navigation Systems



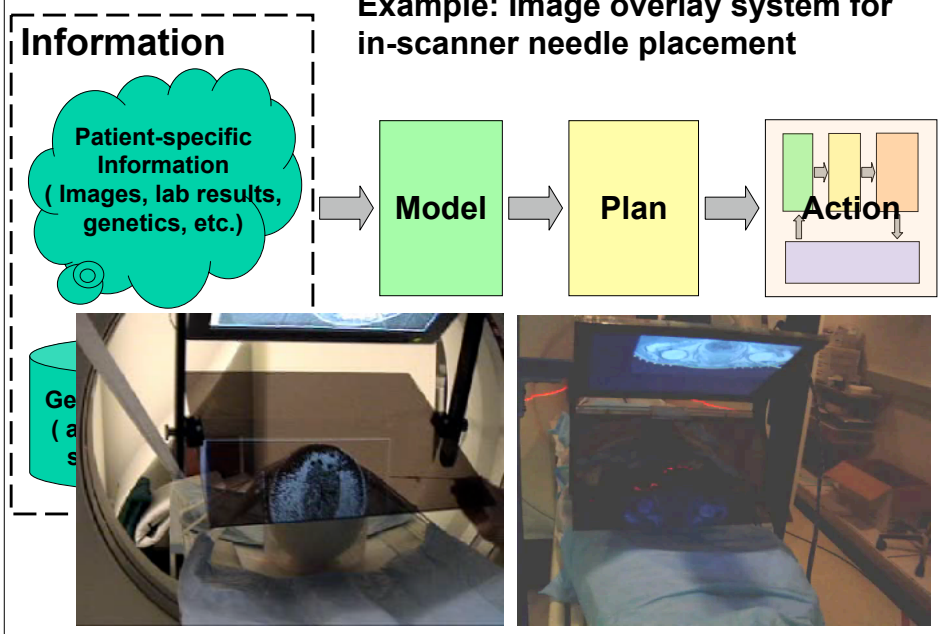
Navigation Systems





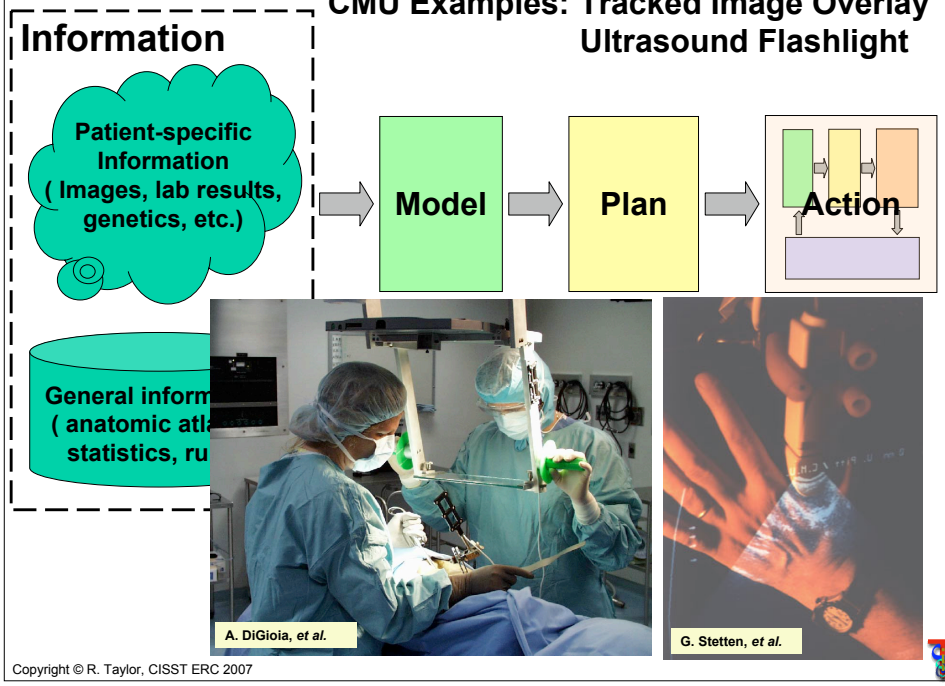
Cutting, Bookstein, Taylor, *et al.*

Example: Image overlay system for in-scanner needle placement

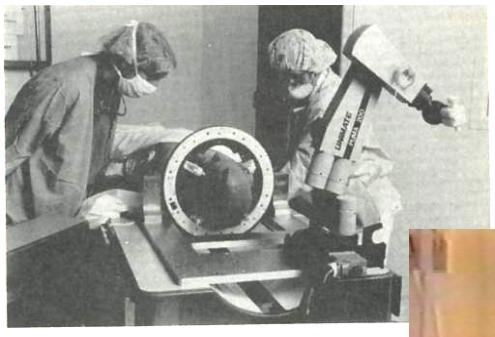


Fischer, Deguet, Csoma, Taylor, Sauer, Iorchidata, Masamune, Zinreich, Fichtinger, …

CMU Examples: Tracked Image Overlay Ultrasound Flashlight

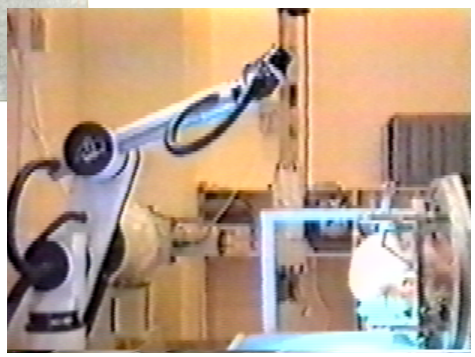


Robotic Needle Guidance

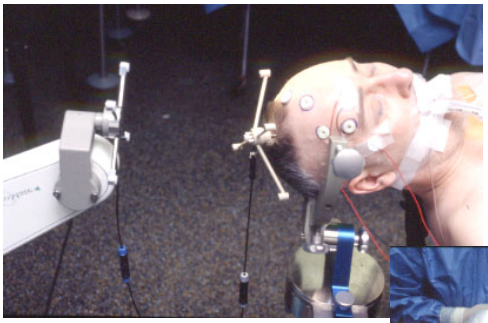


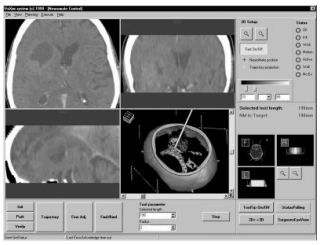
Kwoh, *et al. 1988*

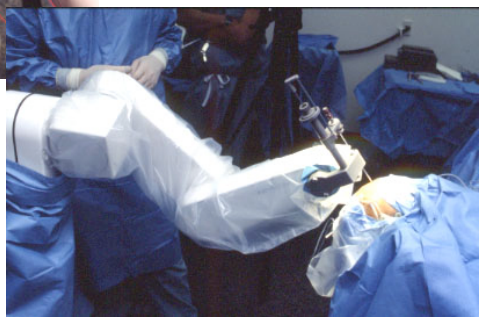
Lavallee, Troccaz, *et al. 1989*



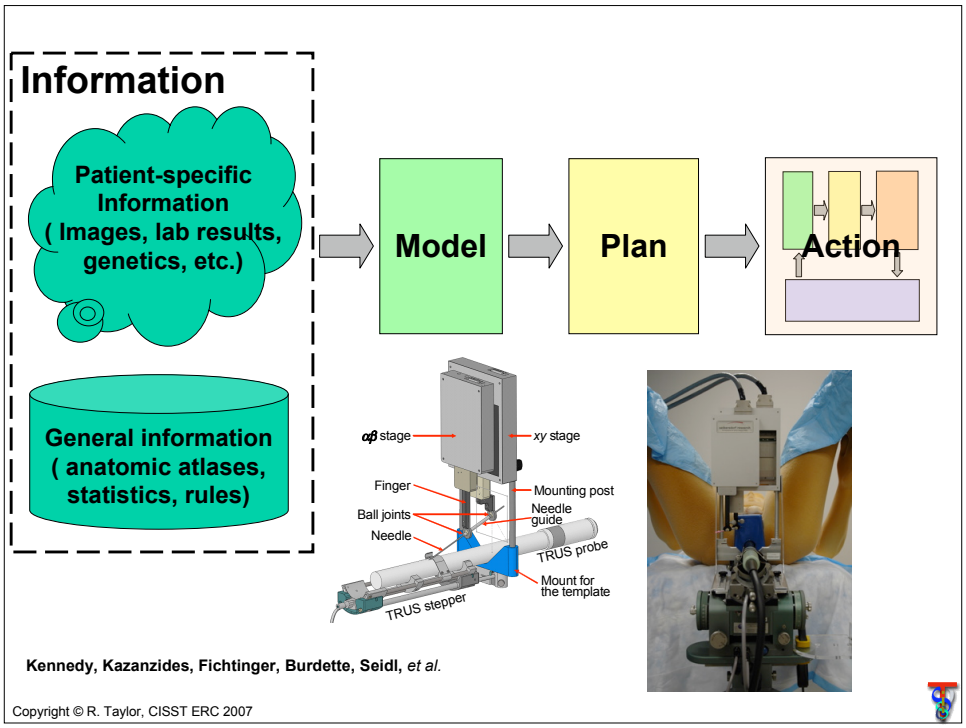
Robotic Needle Guidance







Courtesy: Integrated Surgical Systems


Information
Patient-specific Information (Images, lab results, genetics, etc.)
General information (anatomic atlases, statistics, rules)
Model
Plan
Action
αβ stage
xy stage
Finger
Ball joints
Needle
Mounting post
Needle guide
TRUS probe
Mount for the template
TRUS stepper
Kennedy, Kazanzides, Fichtinger, Burdette, Seidl, et al.
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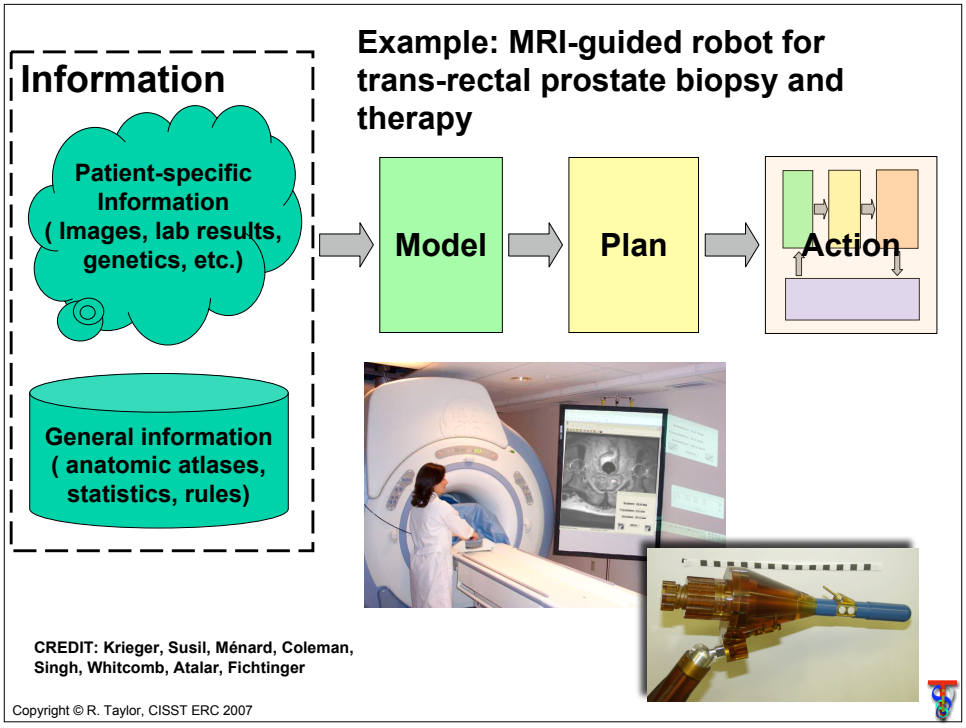
Example: MRI-guided robot for trans-rectal prostate biopsy and therapy
Information
Patient-specific Information (Images, lab results, genetics, etc.)
General information (anatomic atlases, statistics, rules)
Model
Plan
Action
CREDIT: Krieger, Susil, Ménard, Coleman, Singh, Whitcomb, Atalar, Fichtinger
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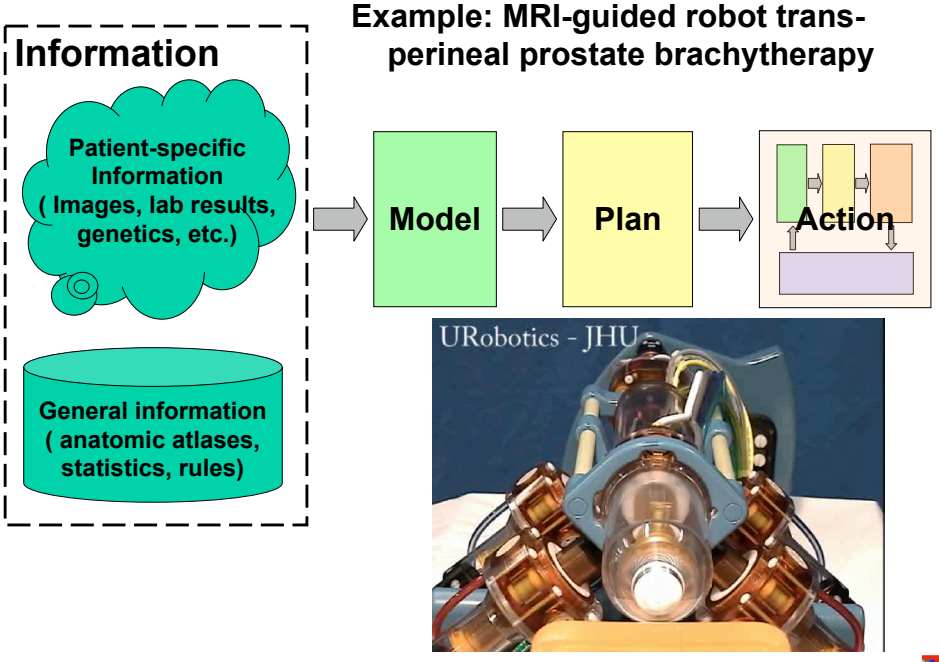
Example: MRI-guided robot trans-perineal prostate brachytherapy

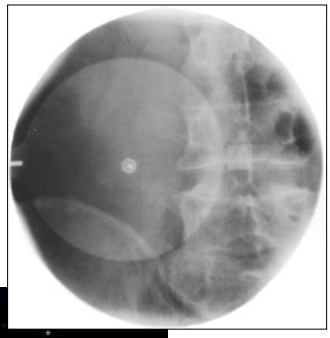


D. Stoainovici, A. Patriciu, *et al.*

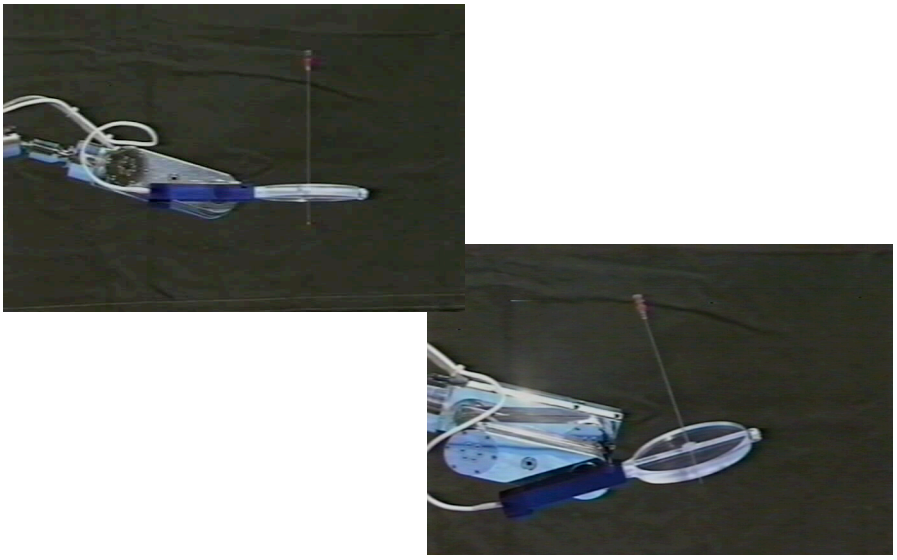
Xray-guidance example:

Percutaneous access to kidney

- Radiolucent needle driver
- Robot aligns needle under x-ray fluoroscopy guidance
- Has been done both locally and remotely

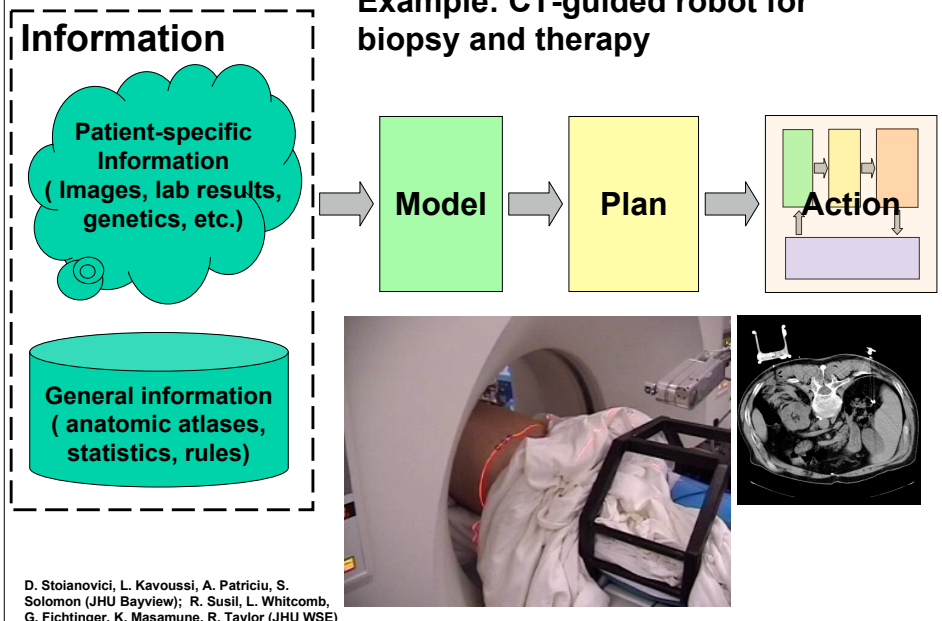


RCM Robot with Radiolucent Needle Driver



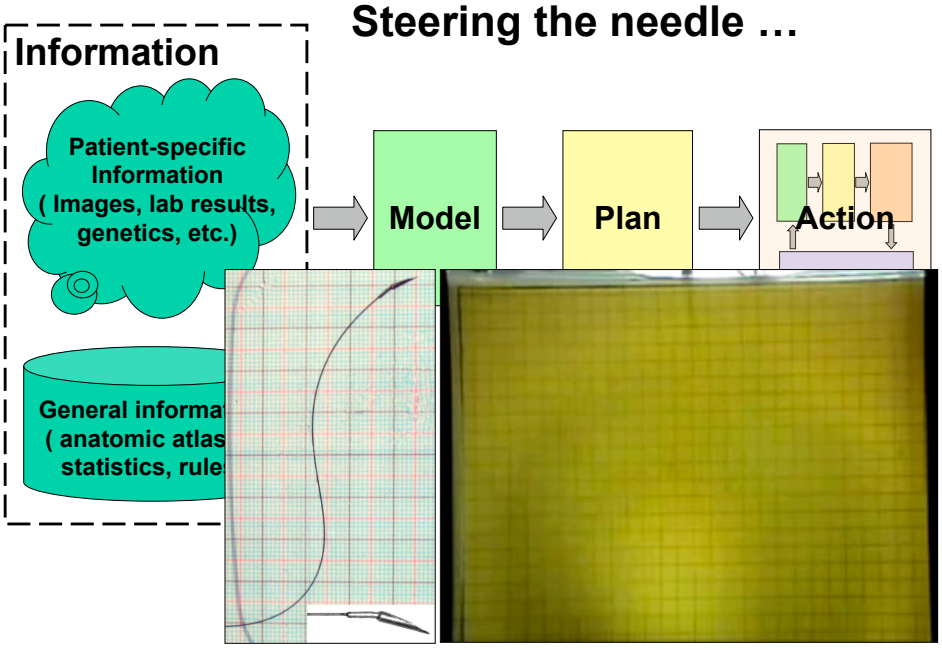
Stoianovici, Taylor, Whictomb, *et al.*

Example: CT-guided robot for biopsy and therapy



D. Stoianovici, L. Kavoussi, A. Patriciu, S. Solomon (JHU Bayview); R. Susil, L. Whitcomb, G. Fichtinger, K. Masamune, R. Taylor (JHU WSE)

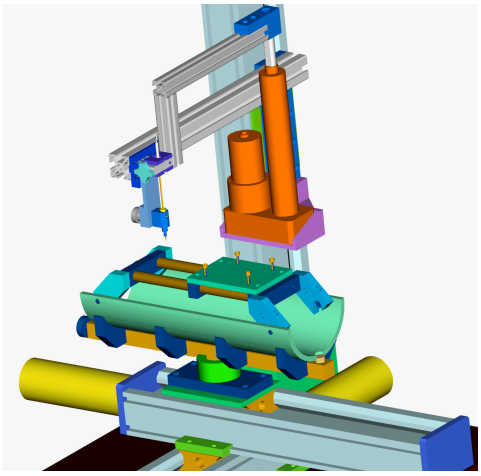
Steering the needle …



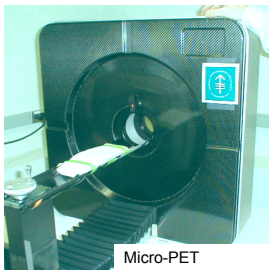
CMU: Riviere, Engh, *et al.* **JHU:** R. Webster, A. Okamura, *et al.*

Robotic Needle Placement in Rodents

P. Kazanzides, G. Fichtinger, C. Ling



Credit: Jack Li, I. Iordachita

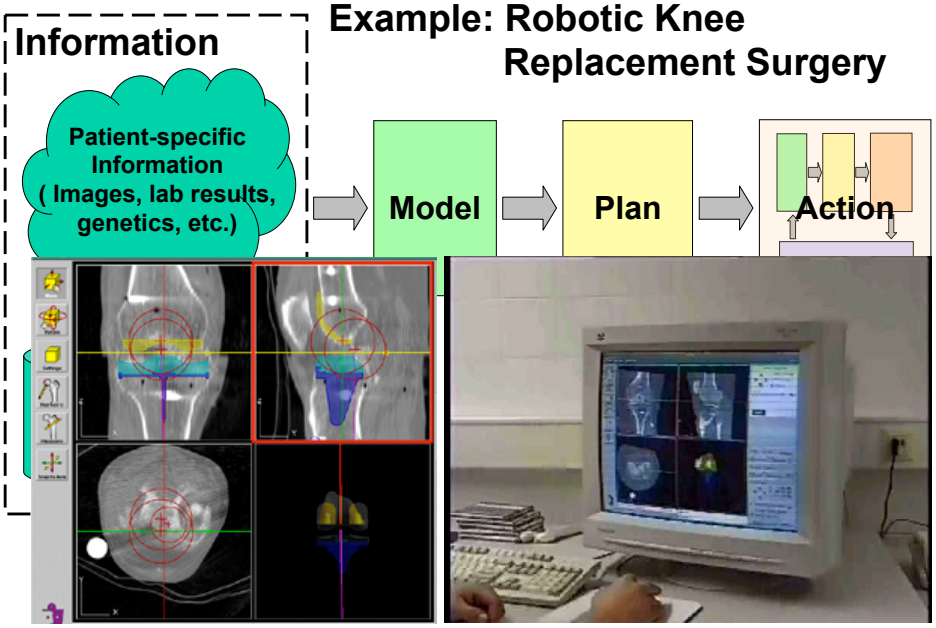


Micro-PET scanner

Courtesy of MSKCC

Research contract from Sloan Kettering

Example: Robotic Knee Replacement Surgery

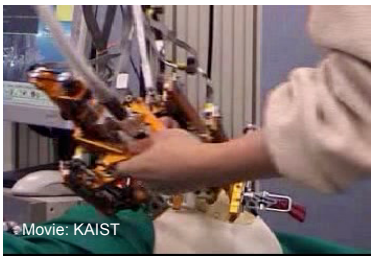


Photos: Integrated Surgical Systems

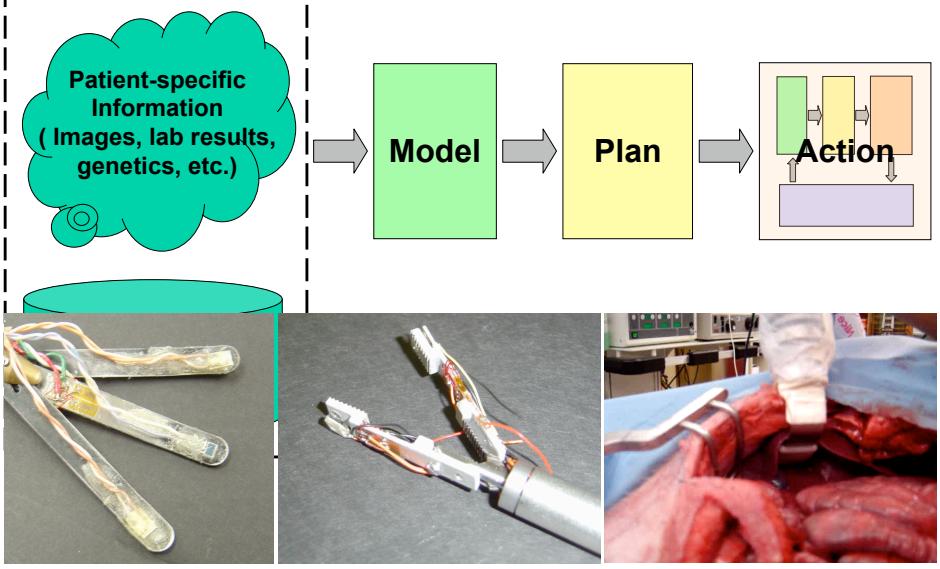
Figure: R. Taylor

Robotic THR & TKR Systems in Research Phases (Partial List)

- Parallel link approaches
  - Aachen (GRIGOS)
  - KAIST
  - Technion
- "Conventional" arms
  - Northwestern
  - U. Washington
  - Rizzoli Institute
  - Tokyo
- Cooperative Control
  - Imperial College (ACROBOT)
  - Grenoble (PaDyc)

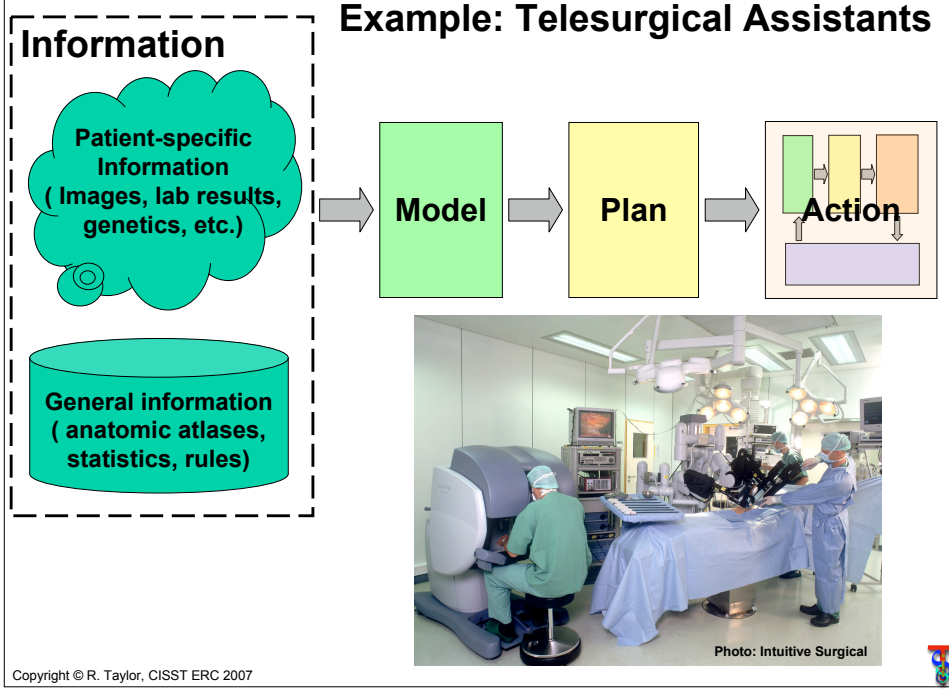


Example: Sensorized Instruments



Fischer, Akinbiyi, Balicki ,Saha, Meireles, Talamini, Marohn, Taylor, *et al.*

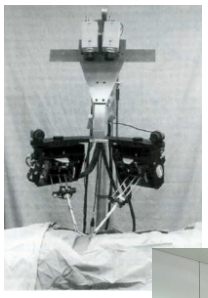
Example: Telesurgical Assistants



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

ISI daVinci system

Human-machine cooperative manipulation in surgery

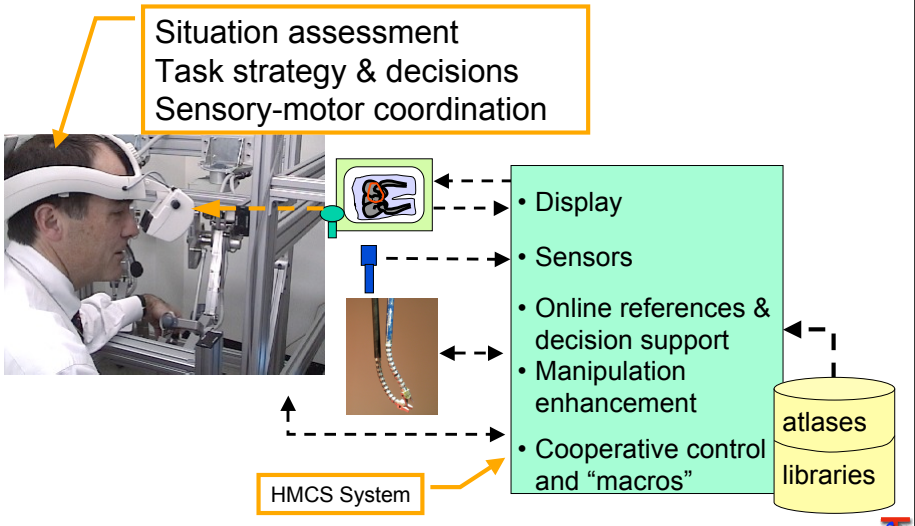
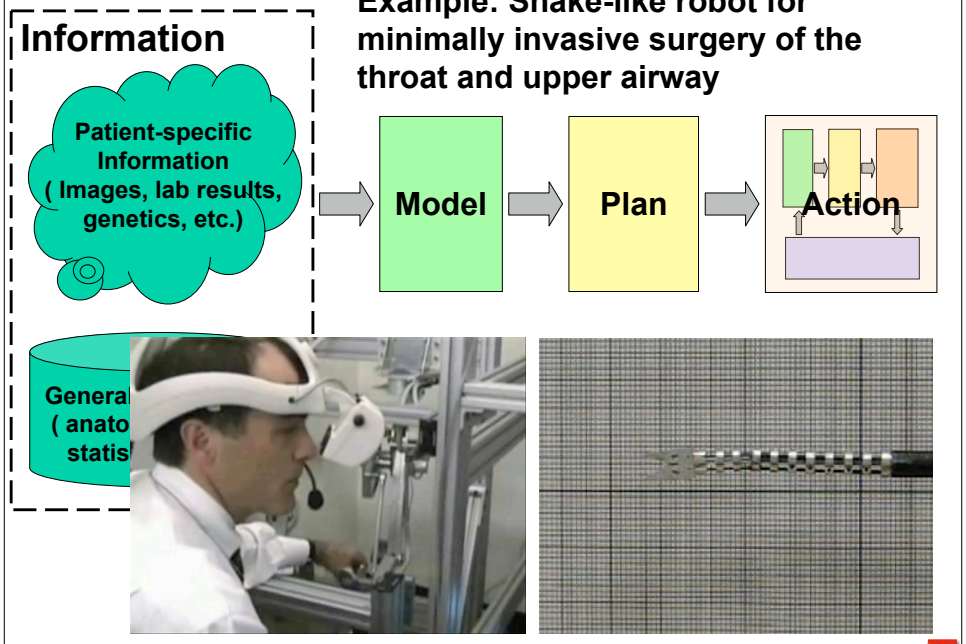


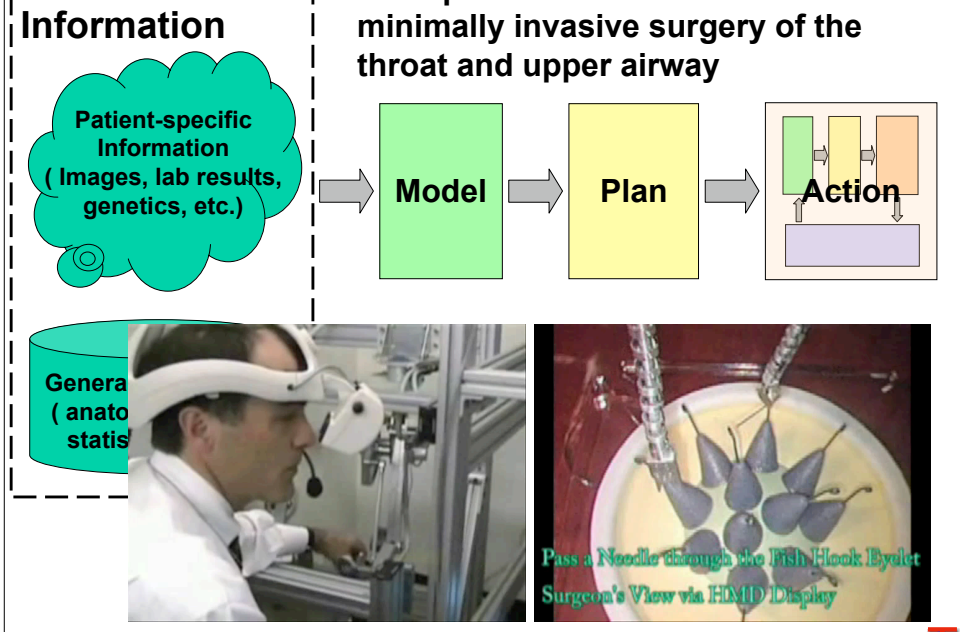
Figure: R. Taylor

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



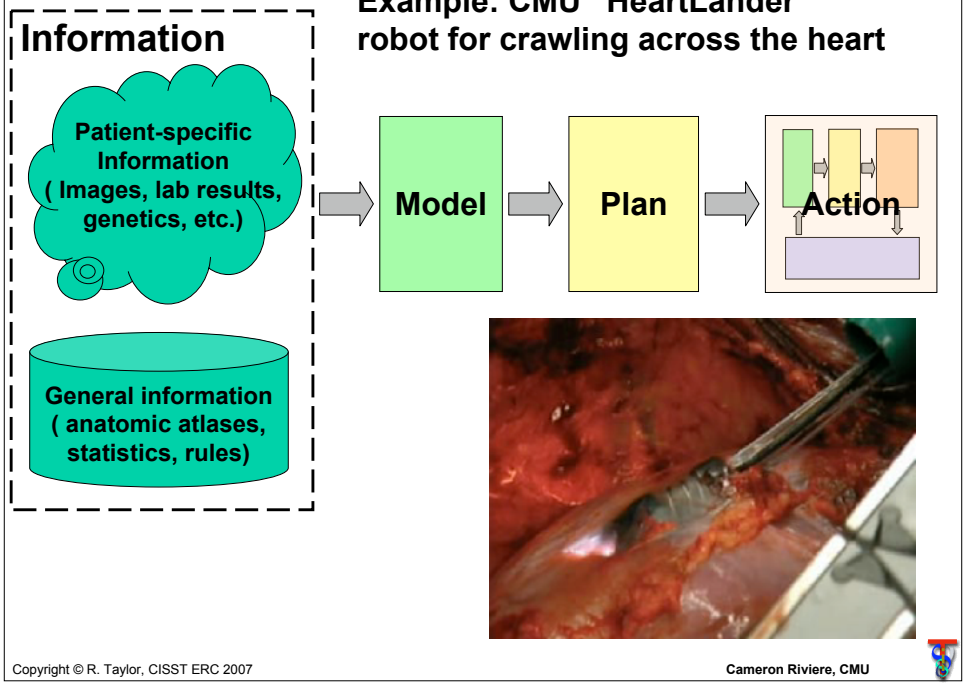
Simaan, Taylor, Flint, Kapoor, Wei , Xu

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



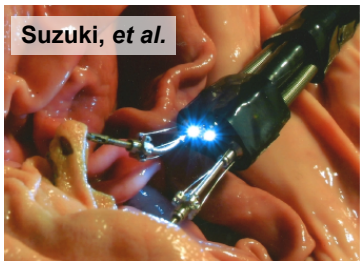
Simaan, Taylor, Flint, Kapoor, Wei , Xu

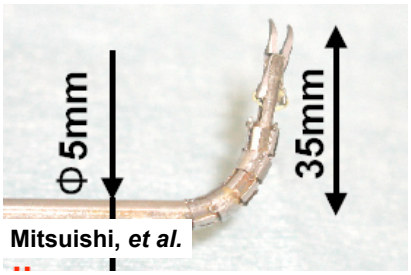
Example: CMU "HeartLander" robot for crawling across the heart

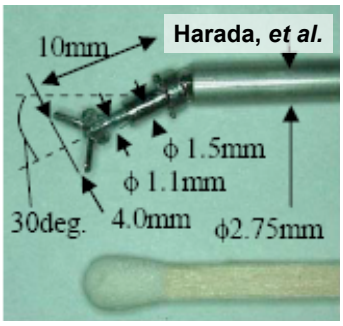


Cameron Riviere, CMU

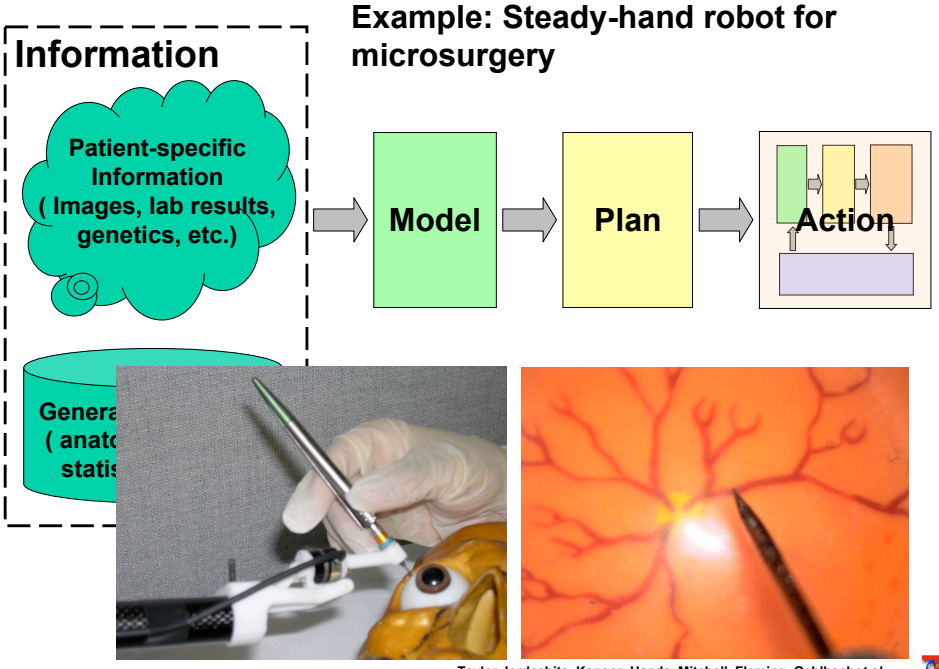
Other examples





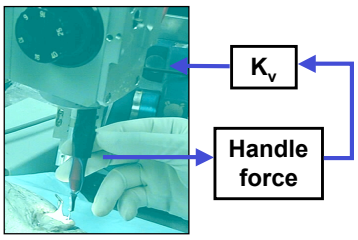


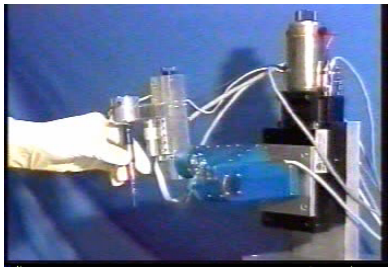
Example: Steady-hand robot for microsurgery



Taylor, Iordachita, Kapoor, Handa, Mitchell, Fleming, Gehlbach*et al.*

Steady Hand Guiding for Microsurgery



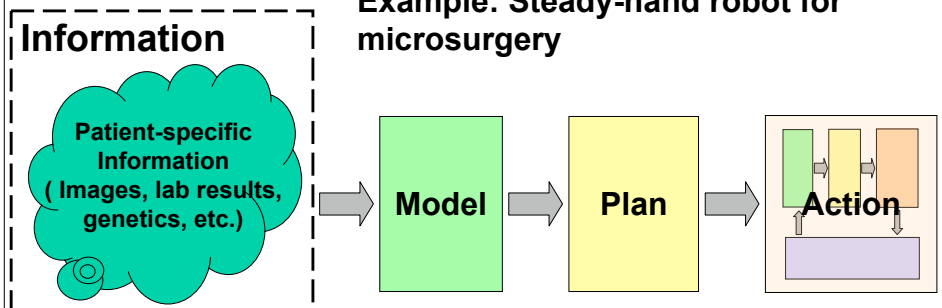


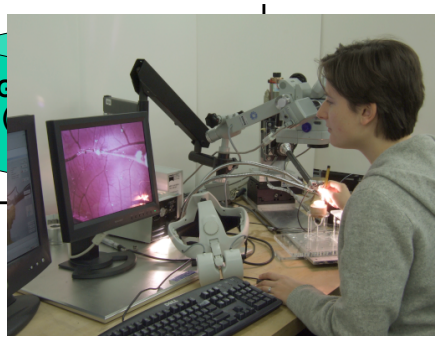
Free hand motion

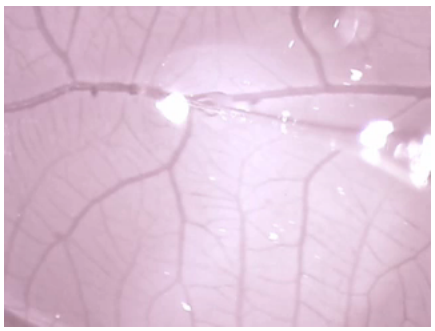
Steady hand motion

R. Taylor, L. Whitcomb, P. Jensen, R. Kumar, *et al.*

Example: Steady-hand robot for microsurgery

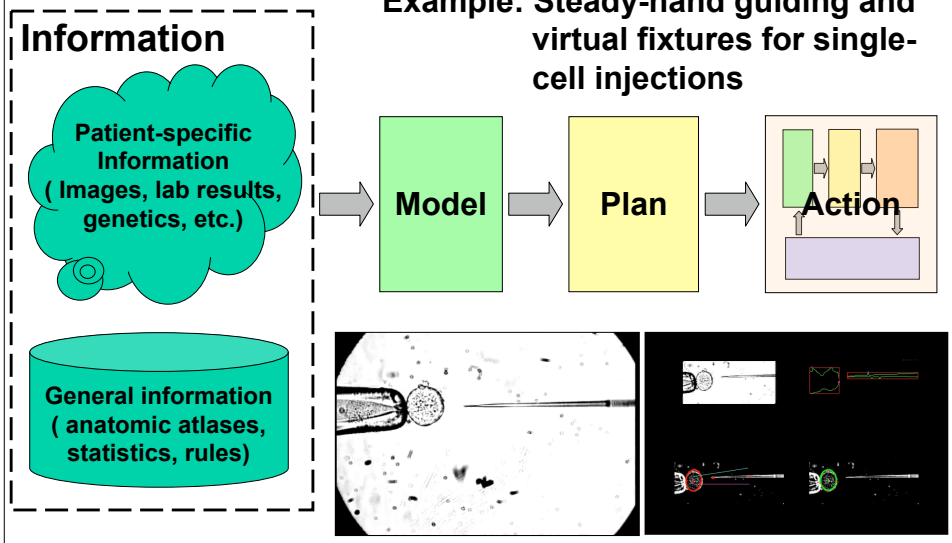






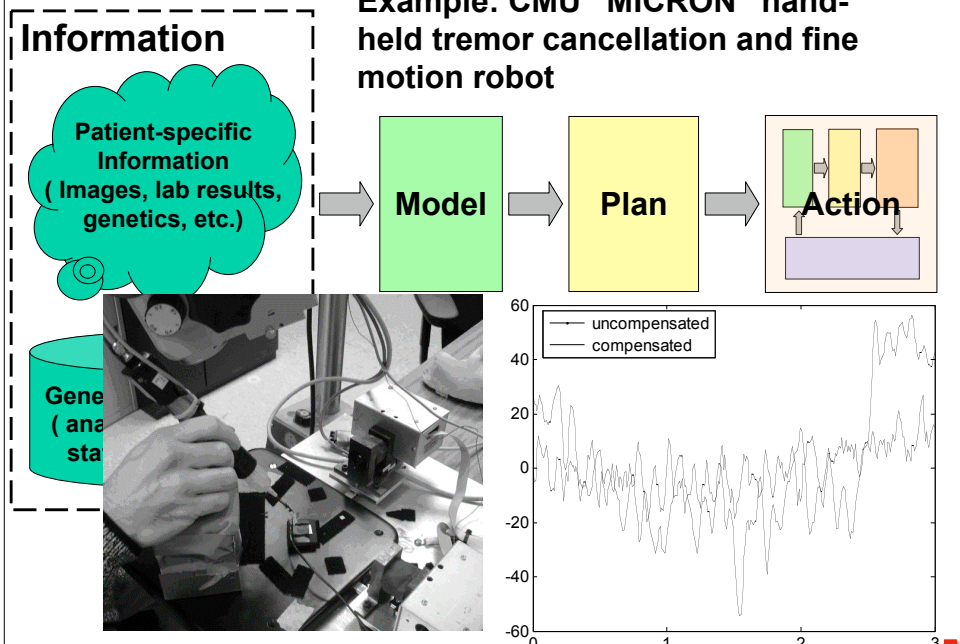
Taylor, Iordachita, Kapoor, Handa, Mitchell, Fleming, Gehlbach*et al.*

Example: Steady-hand guiding and virtual fixtures for single-cell injections



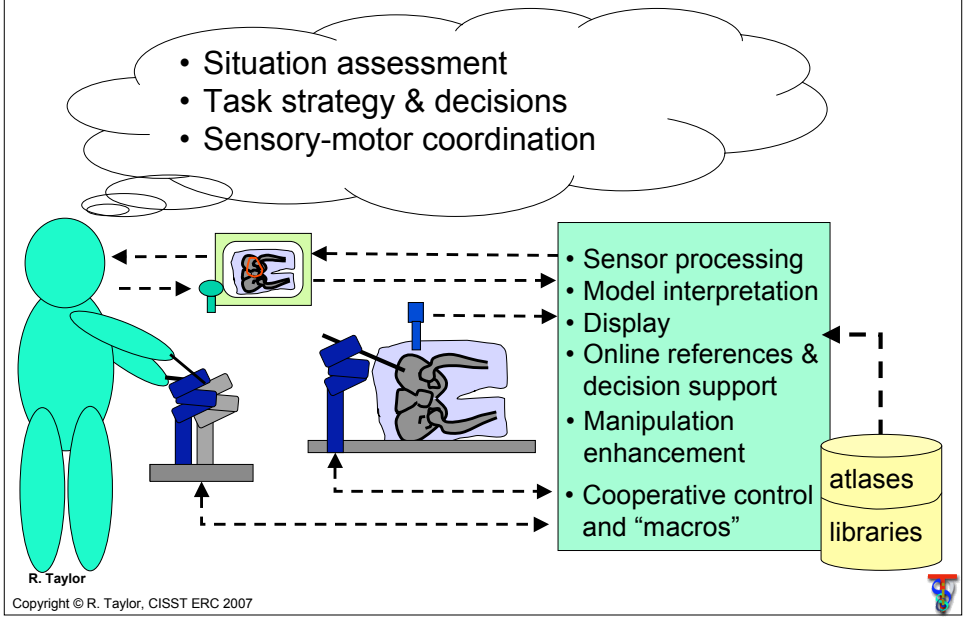
Kapoor, Kumar, Taylor

Example: CMU "MICRON" hand-held tremor cancellation and fine motion robot



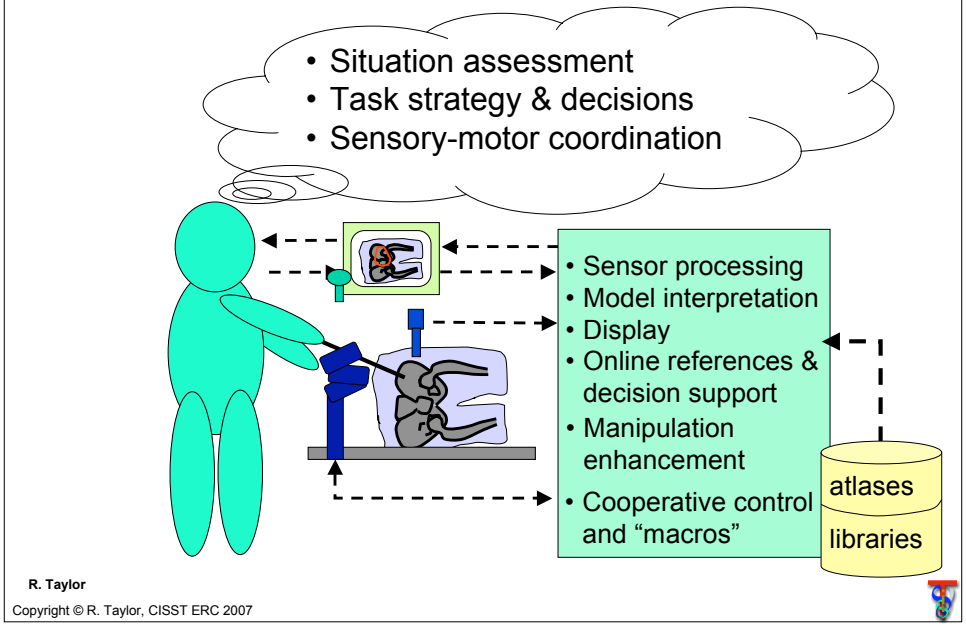
Cameron Riviere, CMU

Evolution to human-machine partnership



R. Taylor

Evolution to human-machine partnership



R. Taylor

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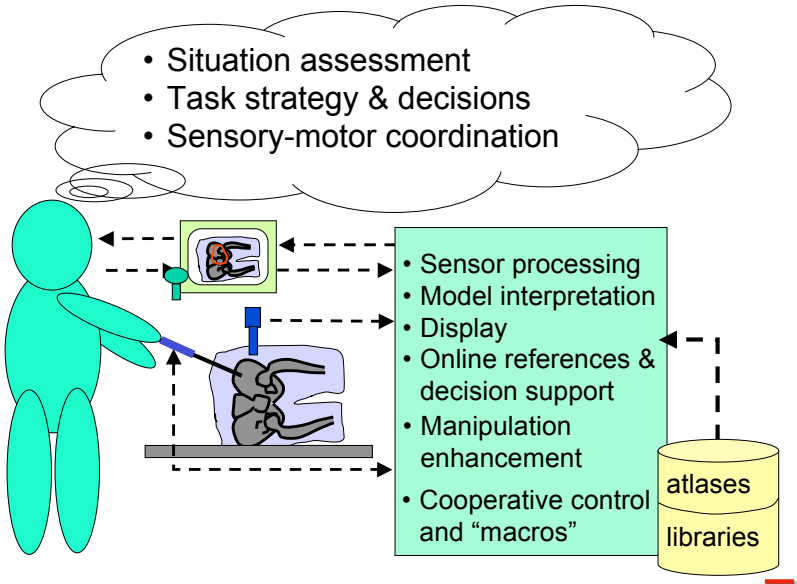
Evolution to human-machine partnership

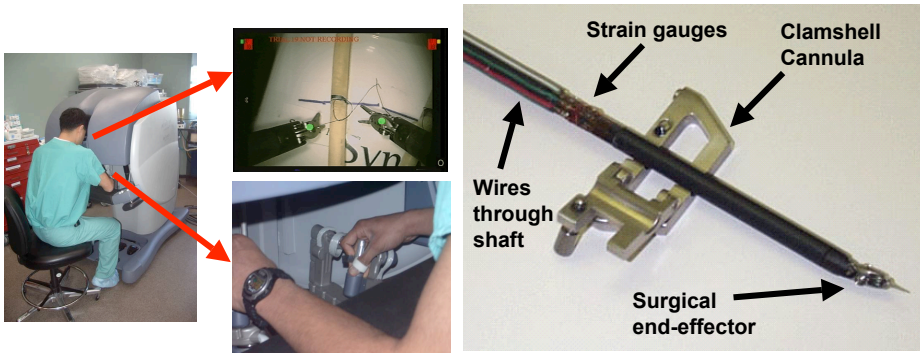


R. Taylor

Enhanced Interfaces for Surgical Robots

IBM/JHU LARS, *circa* 1993-4

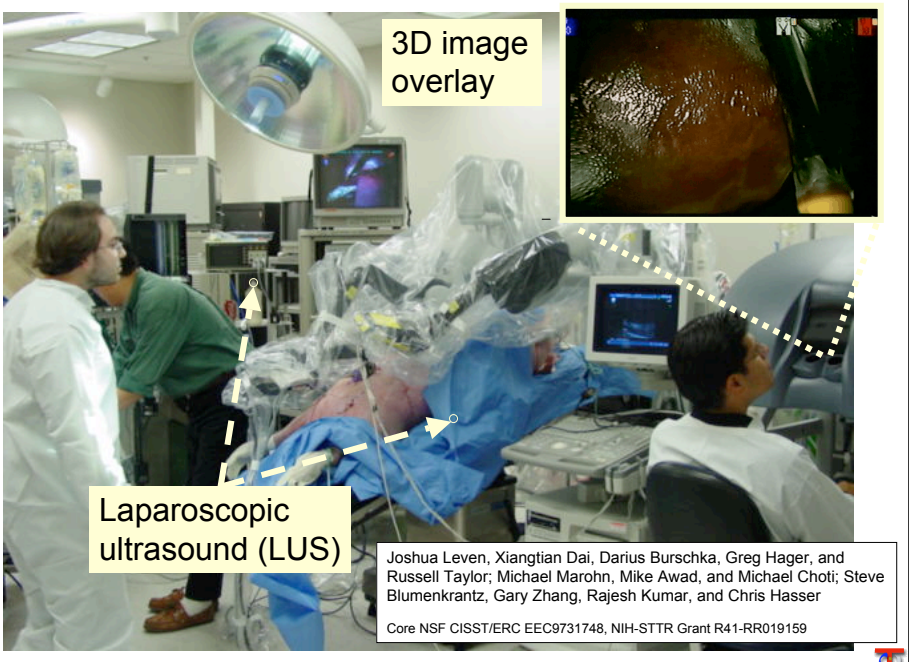
Dynamic Augmented Reality for Sensory Substitution in Robot-Assisted Surgical Systems



Sensory substitution of force information improves performance:

Metric	p-value	Significant
Number of broken sutures	.0111	Y
Standard deviation of forces	.0414	Y
Average peak applied force	.0539	*
Number of loose knots	.0667	*
Average task completion time	.7934	N

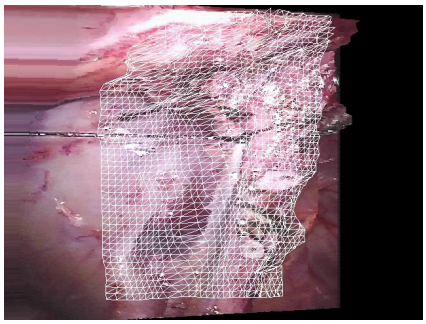
A. Okamura, T. Akinbiyi, *et al.*

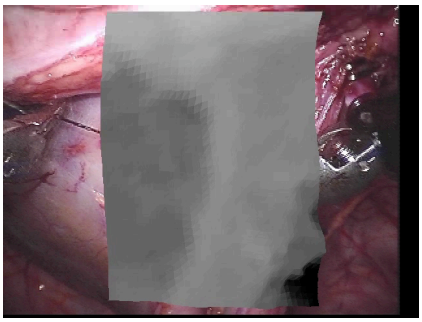


Joshua Leven, Xiangtian Dai, Darius Burschka, Greg Hager, and Russell Taylor; Michael Marohn, Mike Awad, and Michael Choti; Steve Blumenkrantz, Gary Zhang, Rajesh Kumar, and Chris Hasser

Core NSF CISST/ERC EEC9731748, NIH-STTR Grant R41-RR019159

Real Time Deformable Registration and Overlay

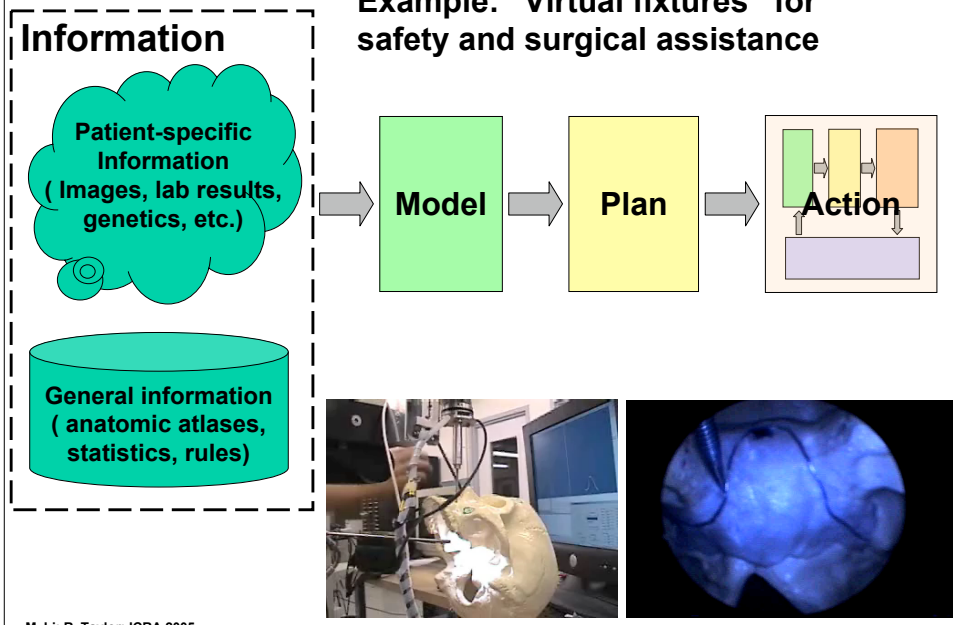




Final registration error of < 1mm except for the area where the tool enters the image

Vagvolgyi, Hager, *et al.*

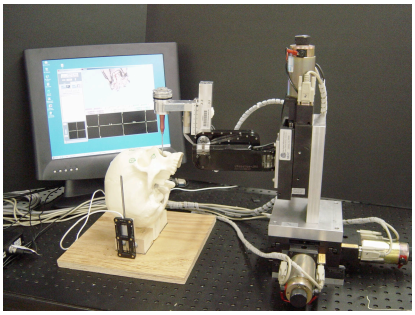
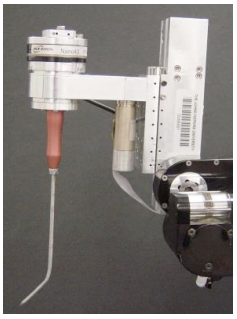
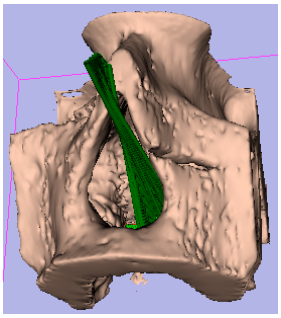
Example: "Virtual fixtures" for safety and surgical assistance

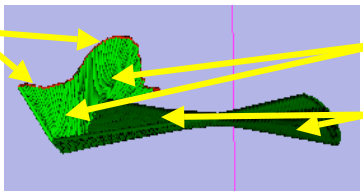


M. Li; R. Taylor; ICRA 2005

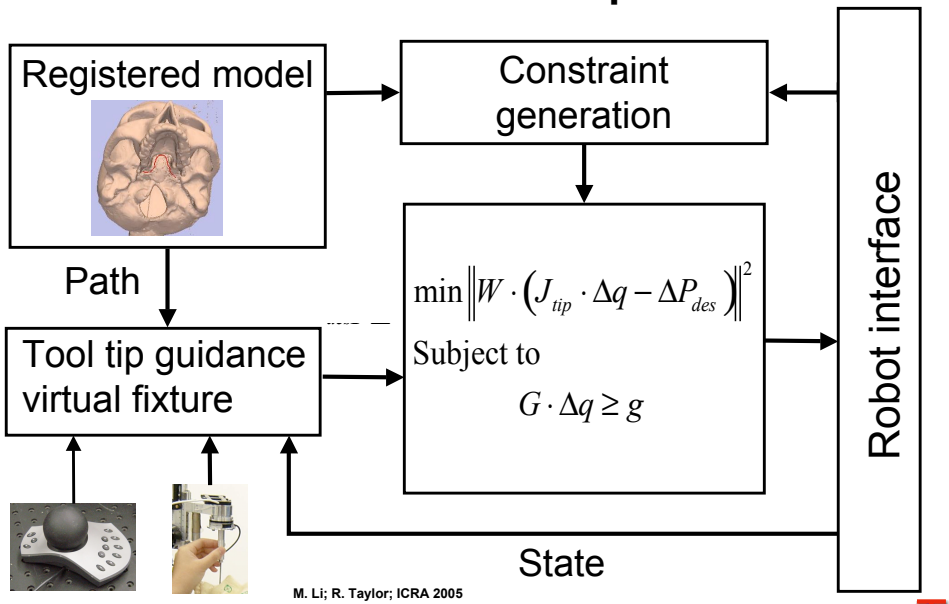
Steady-hand sinus surgery with virtual fixtures derived from CT models

Ming Li, Russell Taylor

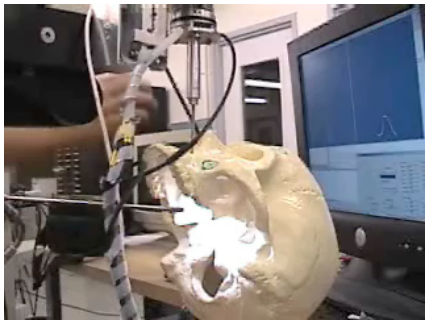




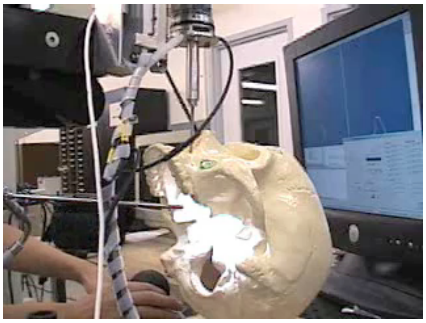


Virtual Fixture Online Implementation

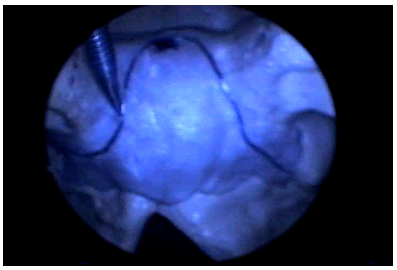


M. Li; R. Taylor; ICRA 2005





Cooperative control guiding



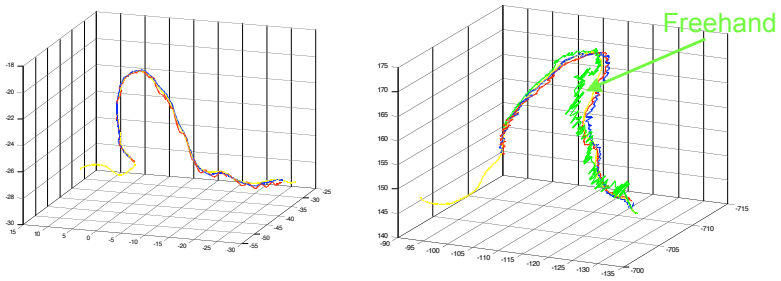
3D mouse guiding

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

M. Li; R. Taylor; ICRA 2005

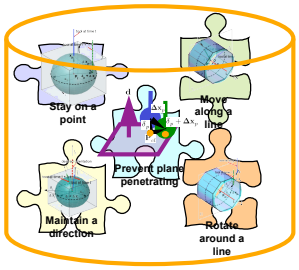
Combine constraints

- **Single frame**

Translational part

$$\begin{bmatrix}\mathbf{H}_p \\ \mathbf{H}_r\end{bmatrix}\mathbf{J}(\mathbf{q})\Delta\mathbf{q} \geq \begin{bmatrix}\mathbf{h}_p \\ \mathbf{h}_r\end{bmatrix}$$

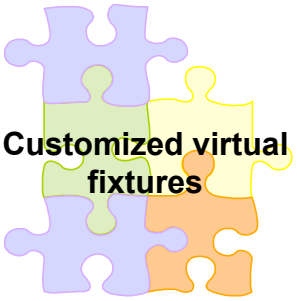
Rotational part



- **Multiple frames**

$$\begin{bmatrix}\mathbf{H}_1 & 0 \\ & \ddots \\ 0 & \mathbf{H}_k\end{bmatrix}\begin{bmatrix}\mathbf{J}_1(\mathbf{q}) \\ \vdots \\ \mathbf{J}_k(\mathbf{q})\end{bmatrix}\Delta\mathbf{q} \geq \begin{bmatrix}\mathbf{h}_1 \\ \vdots \\ \mathbf{h}_k\end{bmatrix}$$

Select one or more



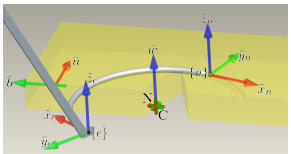
Example: "Virtual fixtures" for suturing assistance

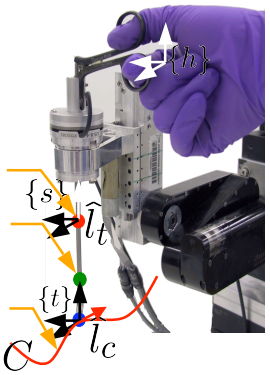
Information

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

General information (anatomic atlases, statistics, rules)

Model → **Plan** → **Action**

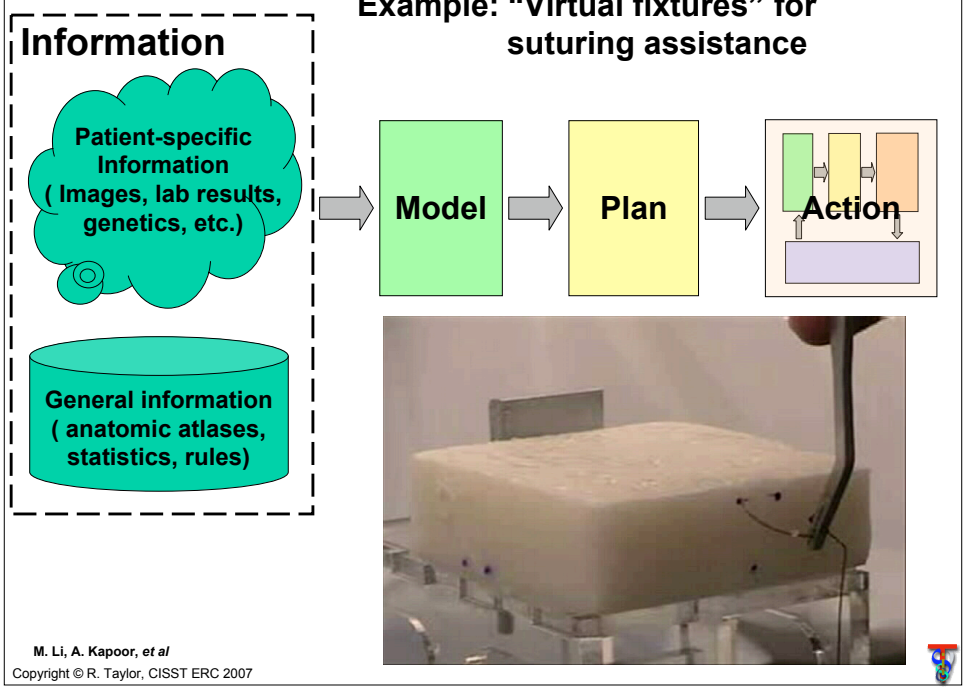




Error (mm)	Entry	Exit
Robot VF	0.63 ± .12	0.77 ±.37
Manual	--	2.1 ± 1.2

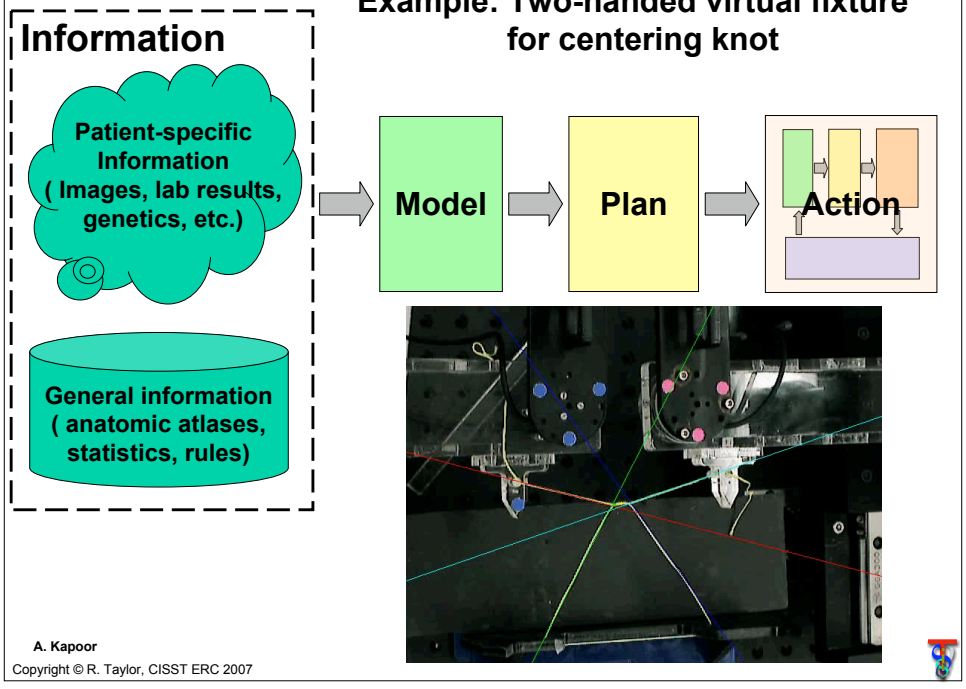
M. Li, A. Kapoor, *et al*

Example: "Virtual fixtures" for suturing assistance

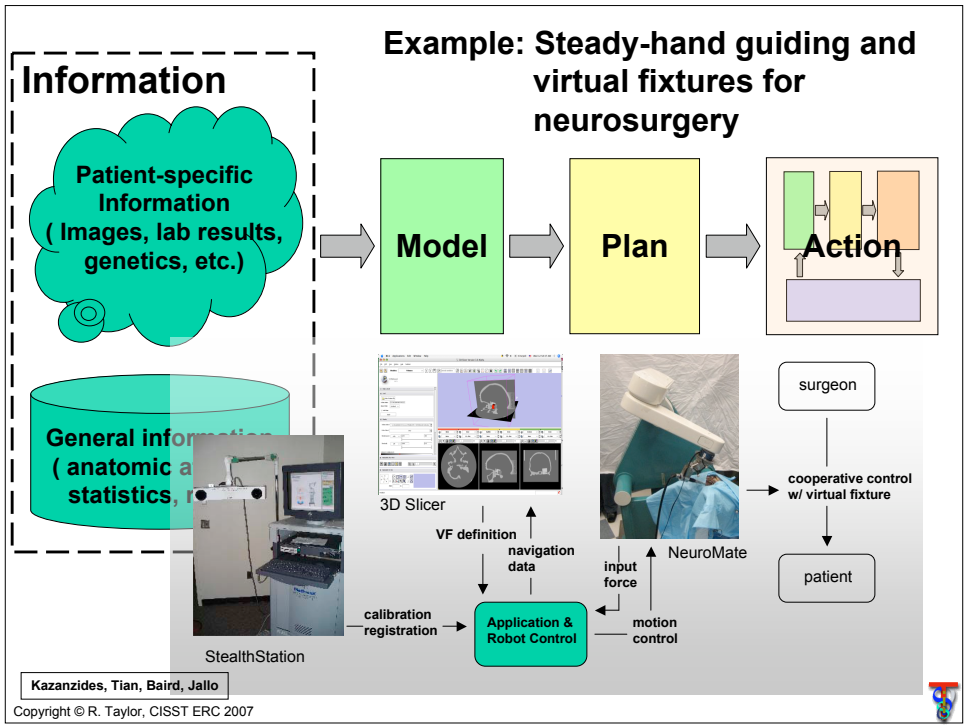


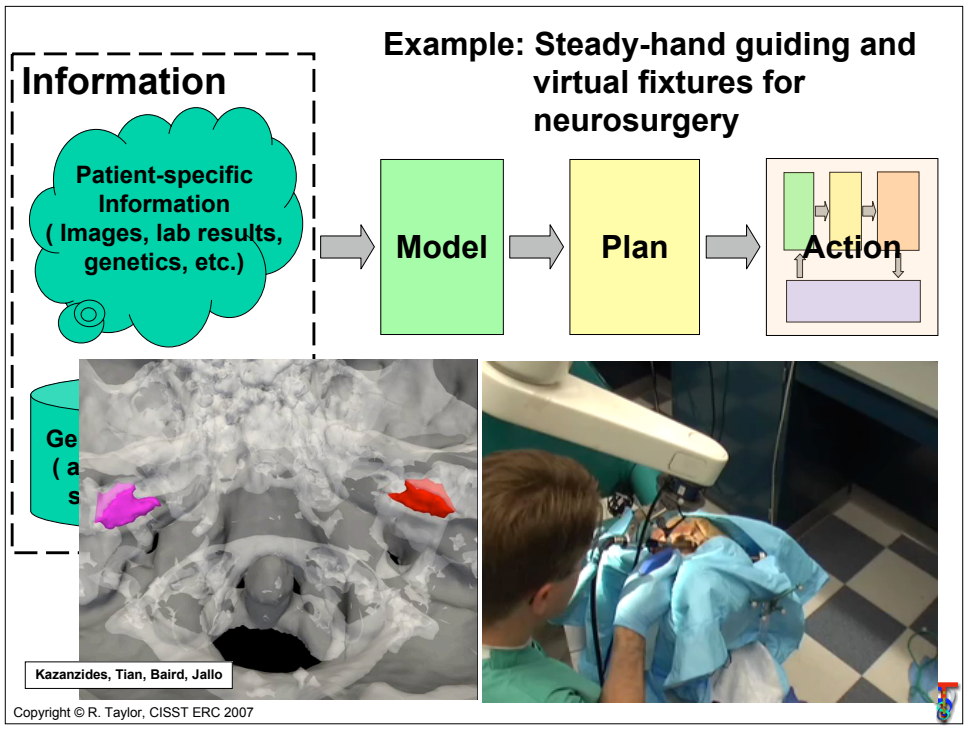
M. Li, A. Kapoor, *et al*

Example: Two-handed virtual fixture for centering knot



A. Kapoor


Example: Steady-hand guiding and virtual fixtures for neurosurgery
Information
Patient-specific Information (Images, lab results, genetics, etc.)
General information (anatomic a statistics, r
Model
Plan
Action
3D Slicer
VF definition
navigation data
calibration registration
Application & Robot Control
input force
motion control
NeuroMate
surgeon
cooperative control w/ virtual fixture
patient
StealthStation
Kazanzides, Tian, Baird, Jallo
Copyright © R. Taylor, CISST ERC 2007


Example: Steady-hand guiding and virtual fixtures for neurosurgery
Information
Patient-specific Information (Images, lab results, genetics, etc.)
Model
Plan
Action
Kazanzides, Tian, Baird, Jallo
Copyright © R. Taylor, CISST ERC 2007

Research Issue: Understanding intent in human-machine cooperation

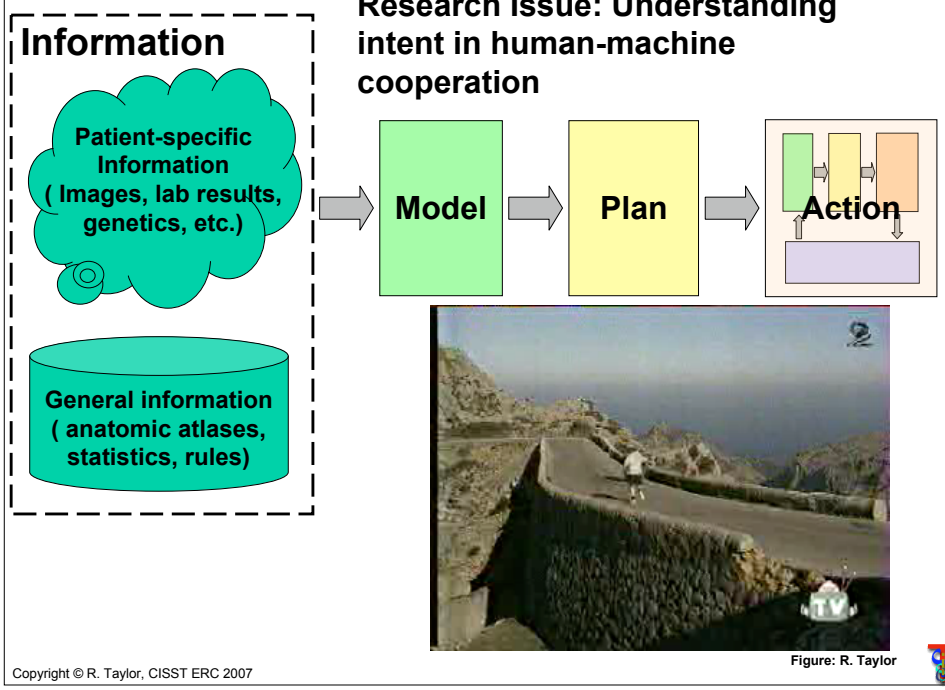
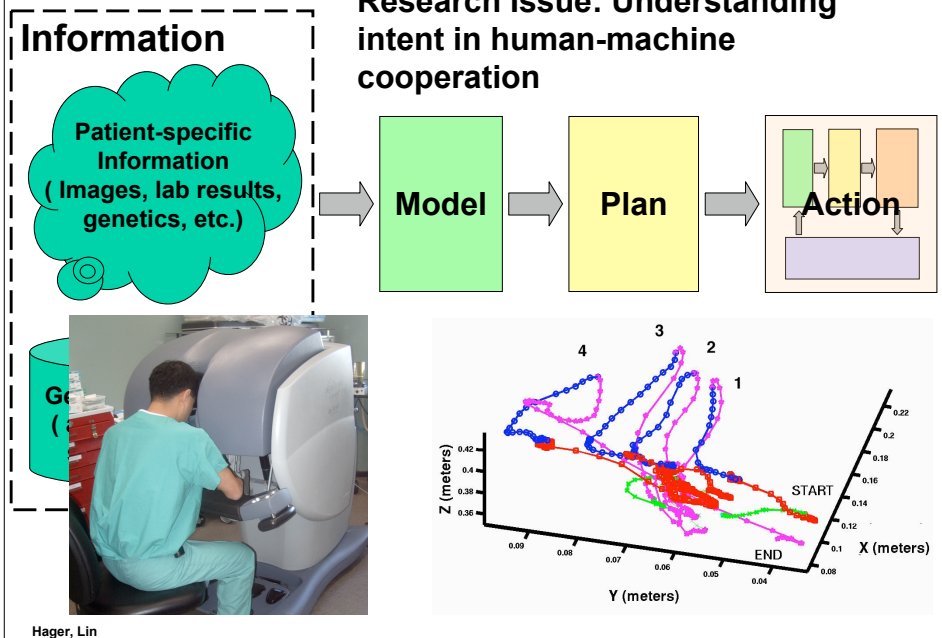


Figure: R. Taylor

Research Issue: Understanding intent in human-machine cooperation



Hager, Lin

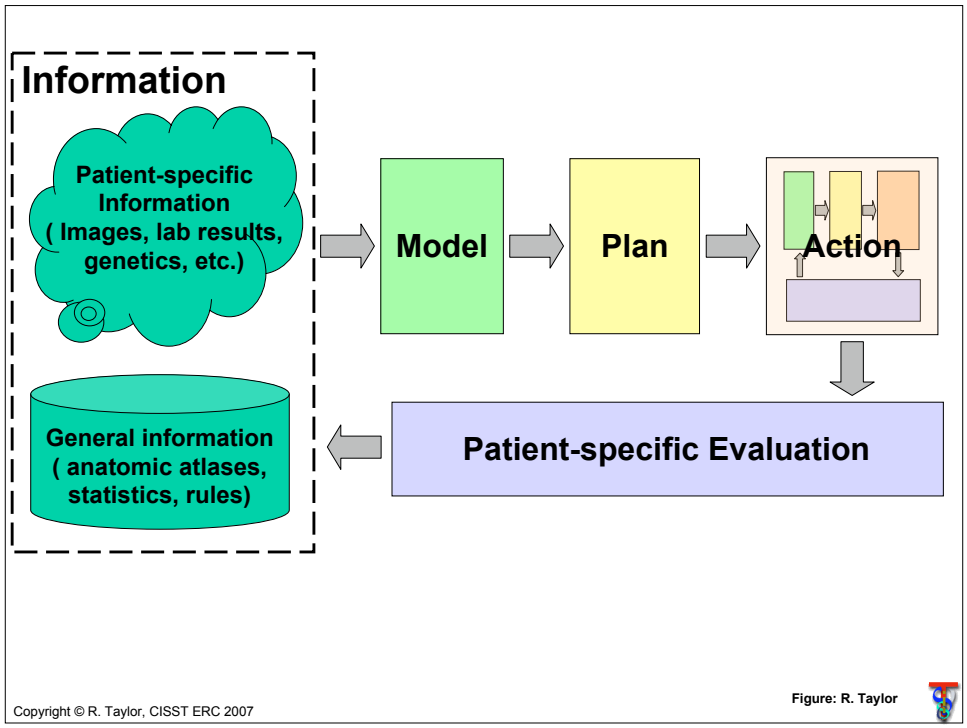
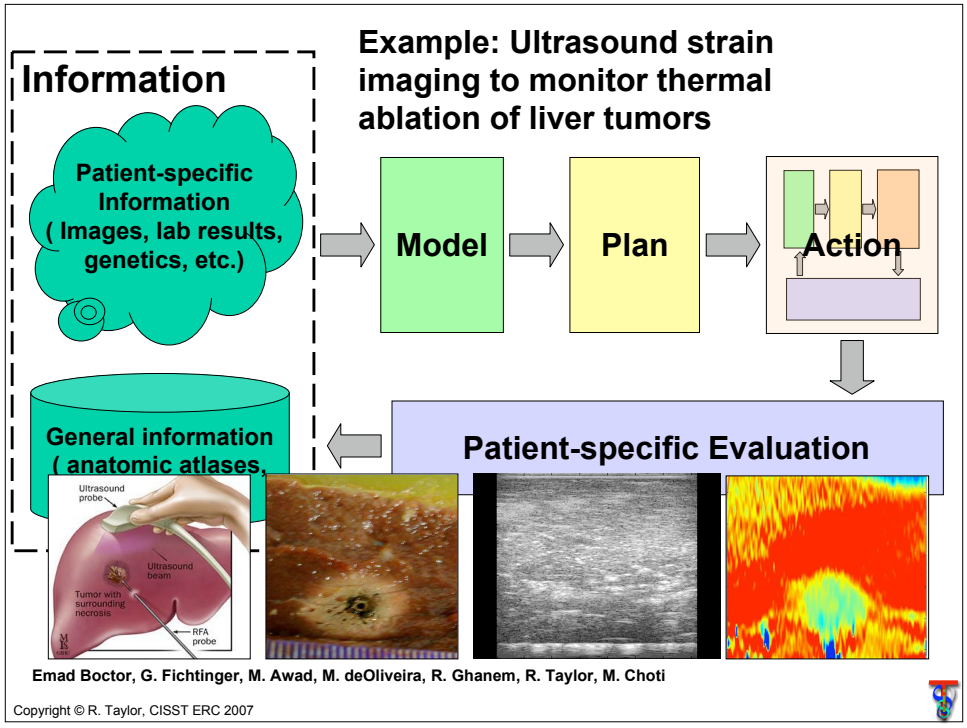
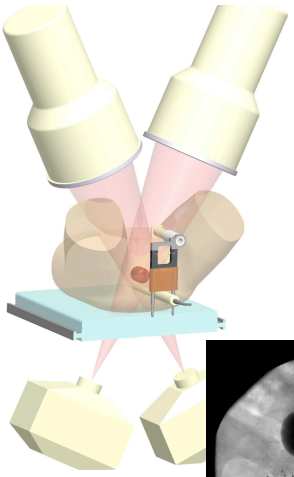


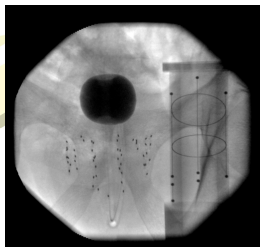
Figure: R. Taylor

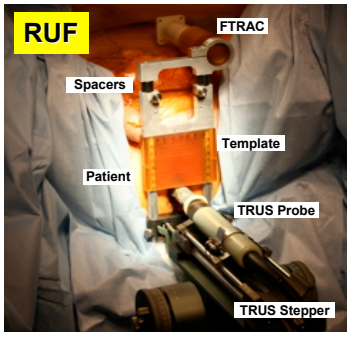


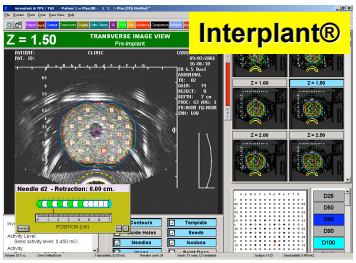
Emad Boctor, G. Fichtinger, M. Awad, M. deOliveira, R. Ghanem, R. Taylor, M. Choti

Fluoroscopic Assessment of Brachytherapy



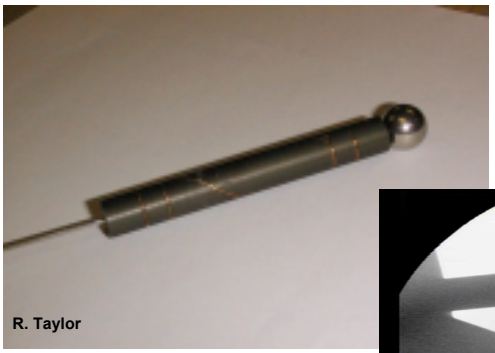


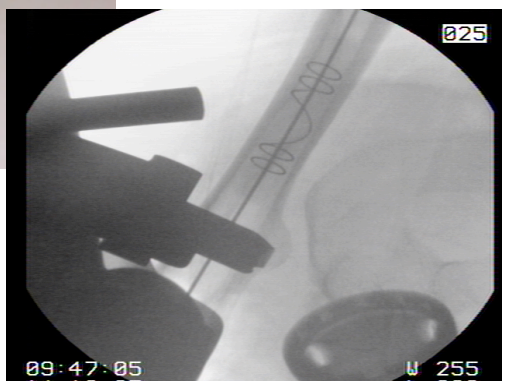




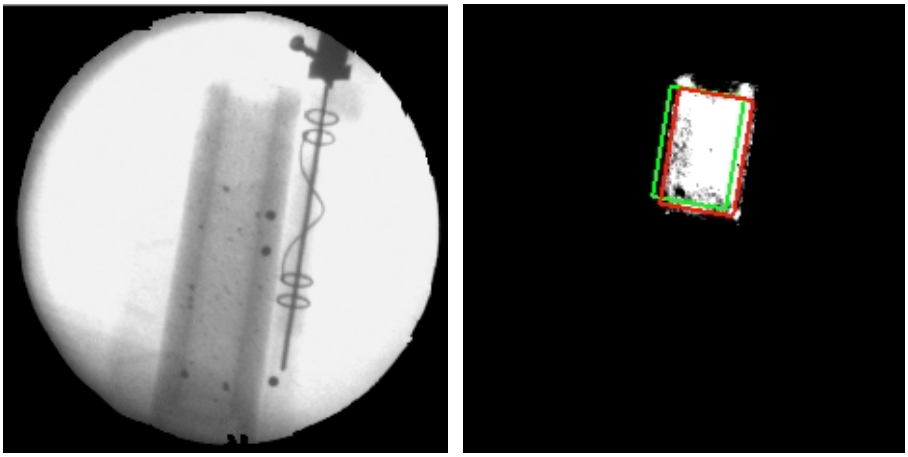
Jain *et* al, MICCAI 2007

X-ray based registration for THR

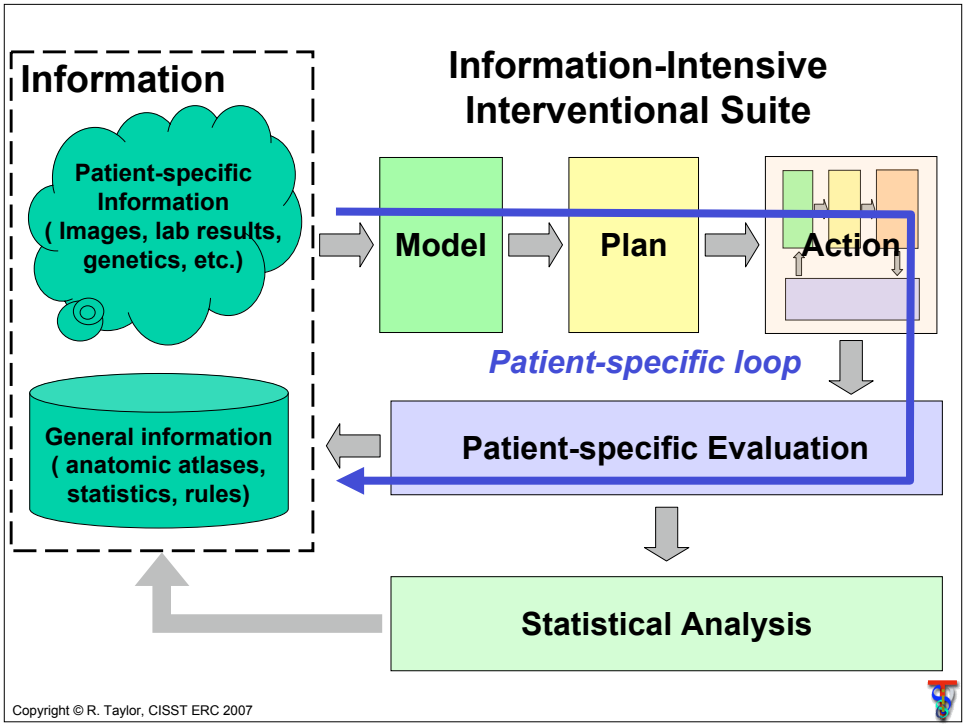


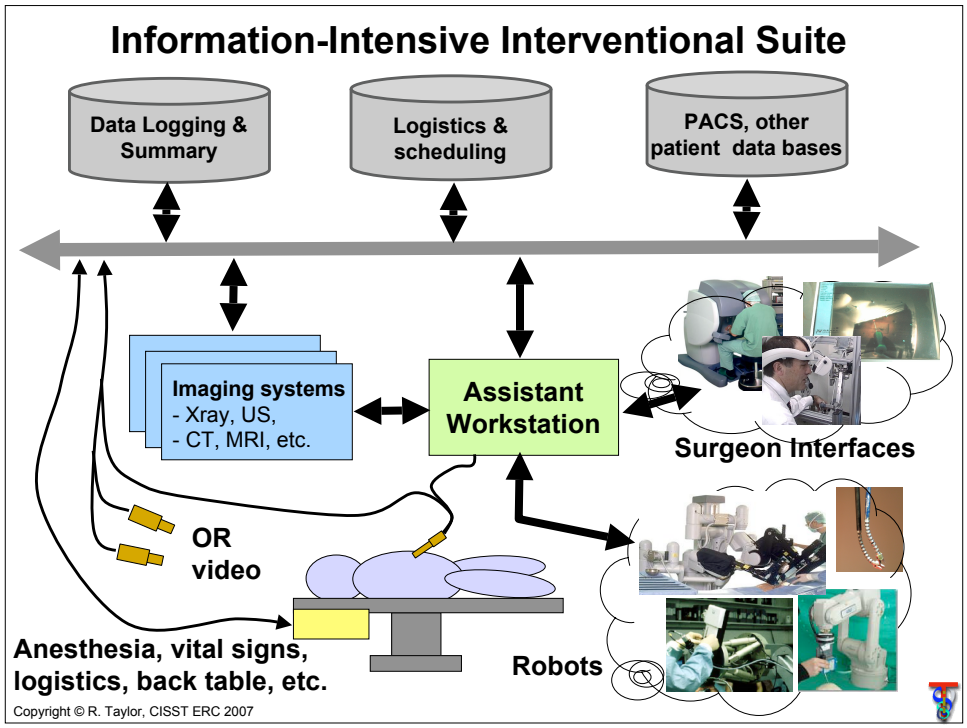


Iterative Cutting to Improve Accuracy



R. Taylor, R. Kumar, R. Goldberg & J. Yao




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
OR video
Anesthesia, vital signs, logistics, back table, etc.
Robots
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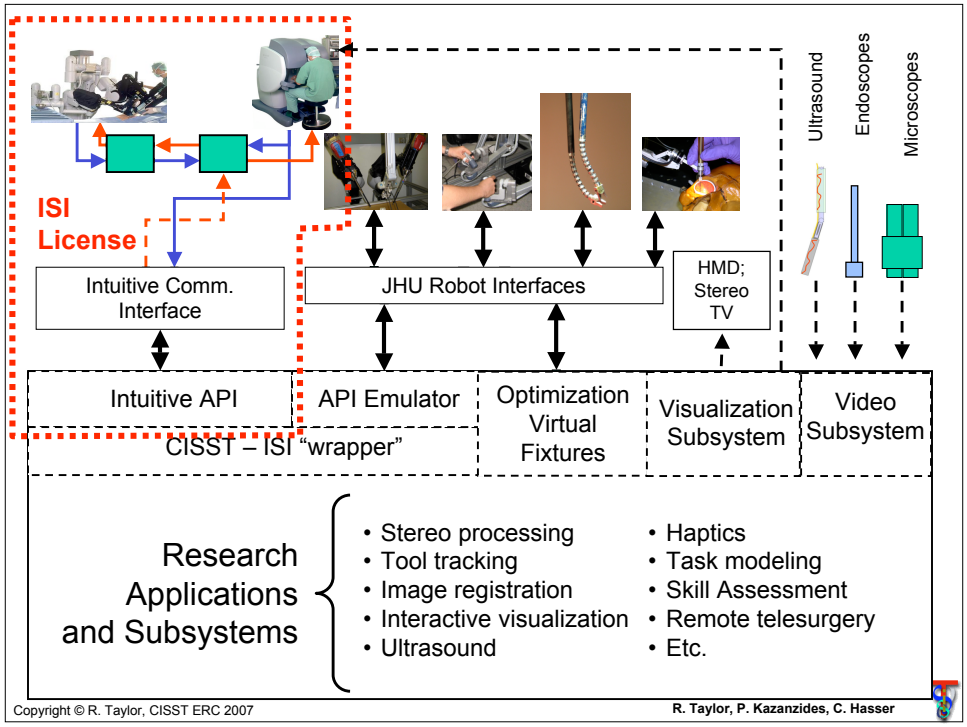
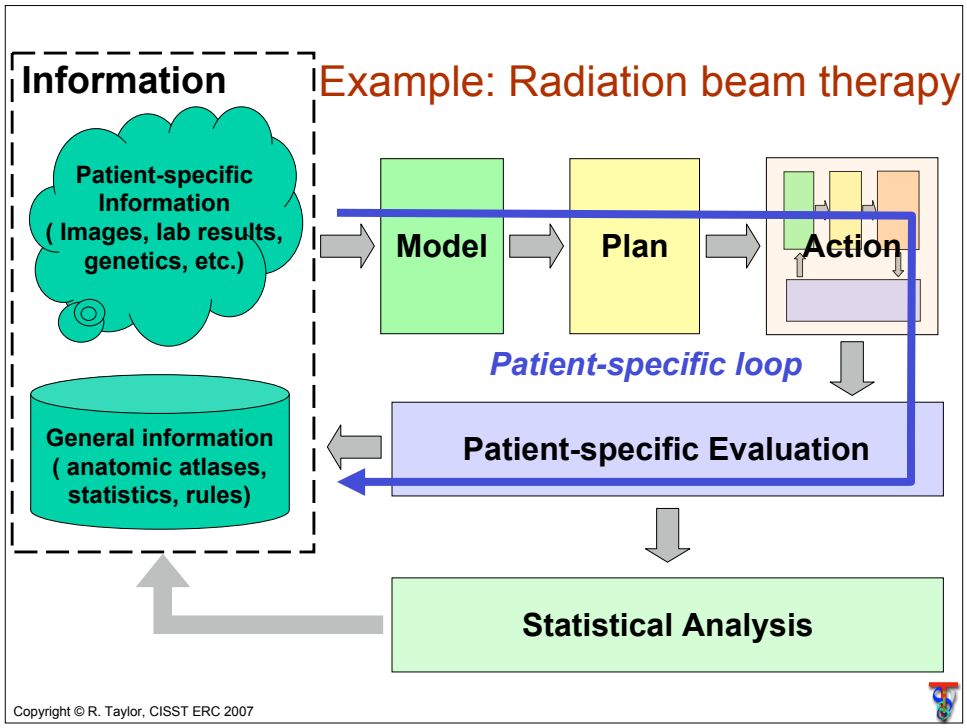
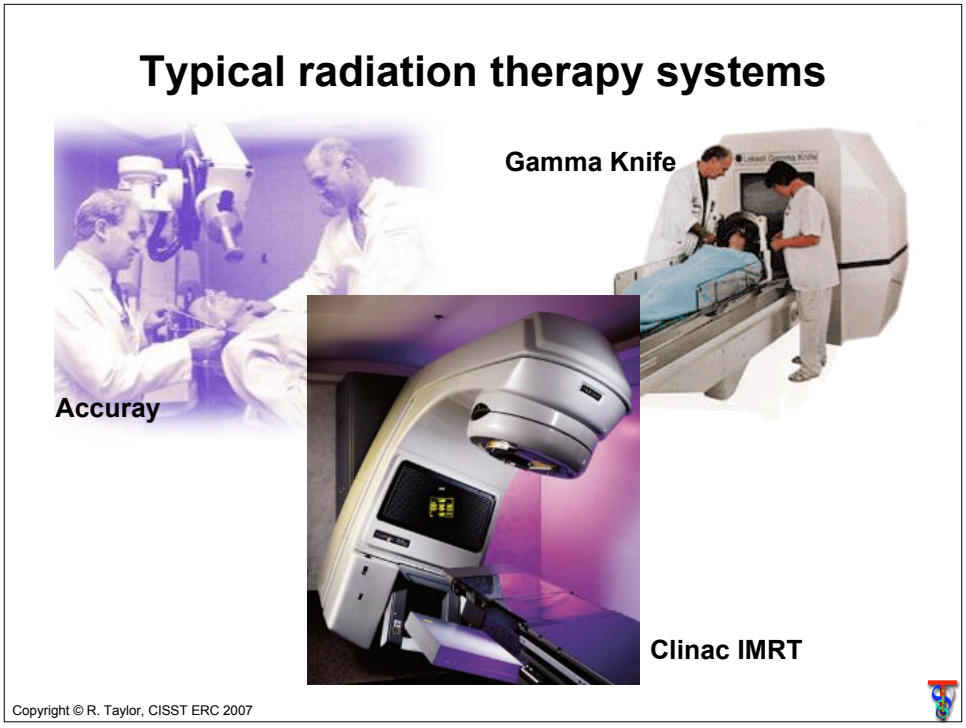

ISI License
Intuitive Comm. Interface
JHU Robot Interfaces
HMD; Stereo TV
Ultrasound
Endoscopes
Microscopes
Intuitive API
API Emulator
Optimization Virtual Fixtures
Visualization Subsystem
Video Subsystem
CISST – ISI "wrapper"
Research Applications and Subsystems
• Stereo processing
• Tool tracking
• Image registration
• Interactive visualization
• Ultrasound
• Haptics
• Task modeling
• Skill Assessment
• Remote telesurgery
• Etc.
Copyright © R. Taylor, CISST ERC 2007
R. Taylor, P. Kazanzides, C. Hasser


Information
Example: Radiation beam therapy
Patient-specific Information (Images, lab results, genetics, etc.)
Model
Plan
Action
Patient-specific loop
General information (anatomic atlases, statistics, rules)
Patient-specific Evaluation
Statistical Analysis
Copyright © R. Taylor, CISST ERC 2007


Typical radiation therapy systems
Gamma Knife
Accuray
Clinac IMRT
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External Beam Radiotherapy

PLANNING (once)

Planning CT

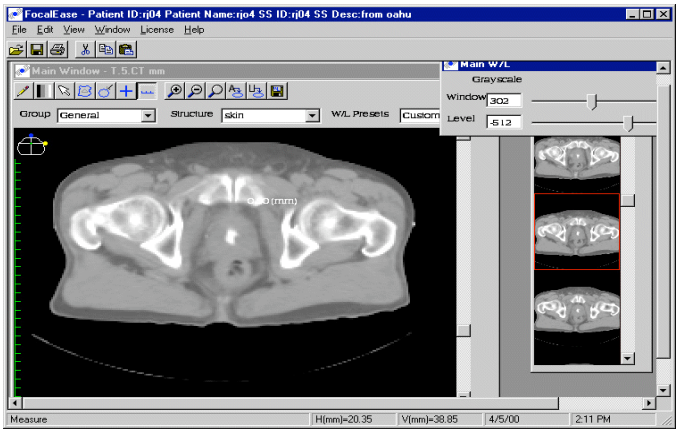
TREATMENT (x40)

aSi portal image

65,000 patients
2.6 million treatments

Figure: G. Fichtinger

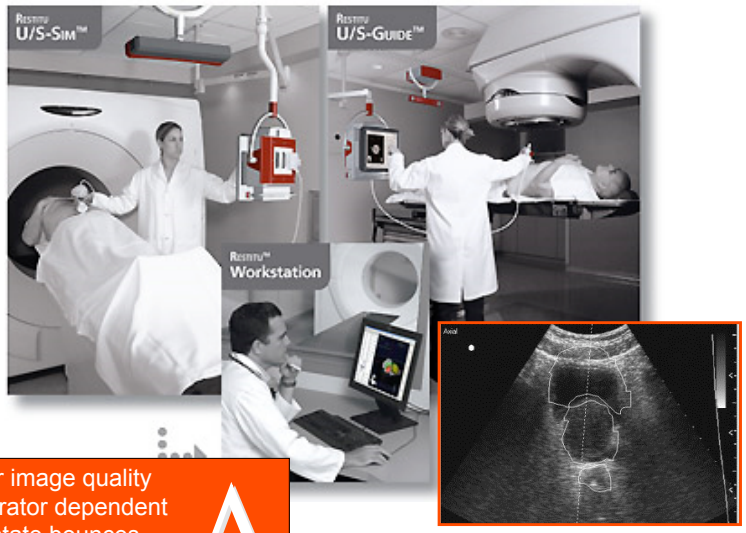
Problem: Dancing Prostate



Inter-fractional Motion from Serial CT – Movement AP ~1cm*

Credit: Andrew Zitman, MD, (MGH)

US Based Prostate Localization?

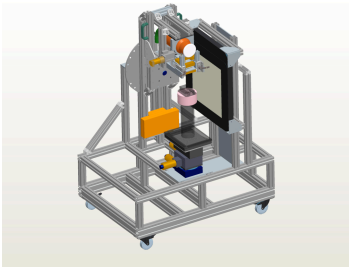


- Poor image quality
- Operator dependent
- Prostate bounces

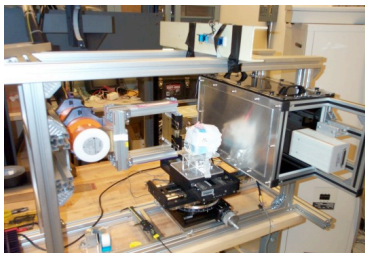
CREDIT: Resonant, RESTITU™ platform

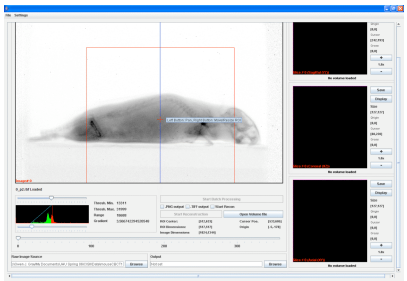
Small Animal Radiation Research Platform

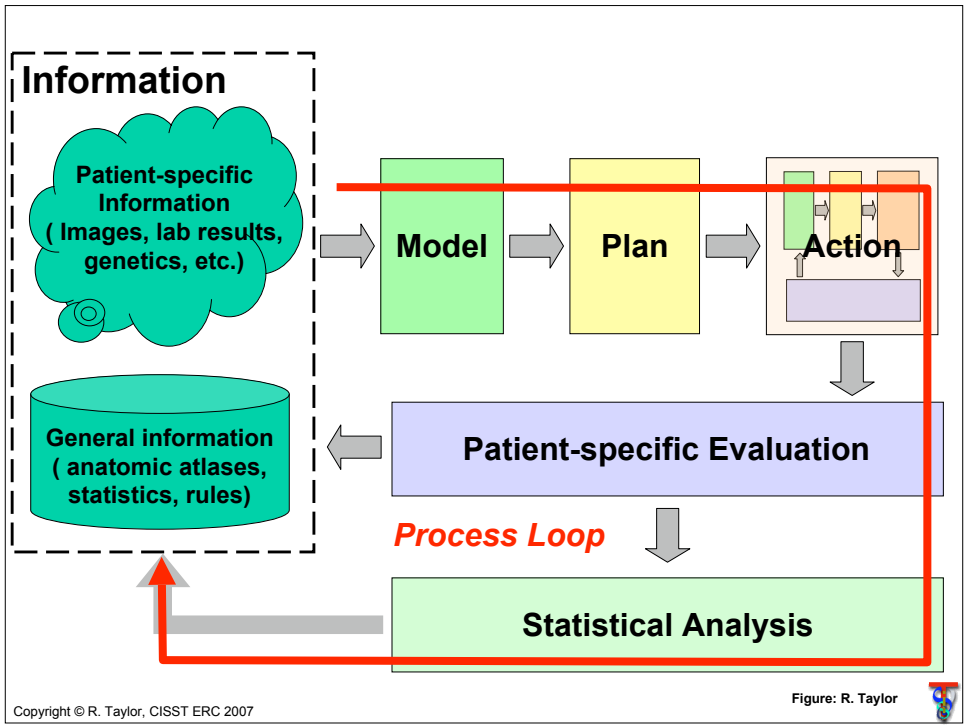
John Wong (PI), Peter Kazanzides, *et al.*

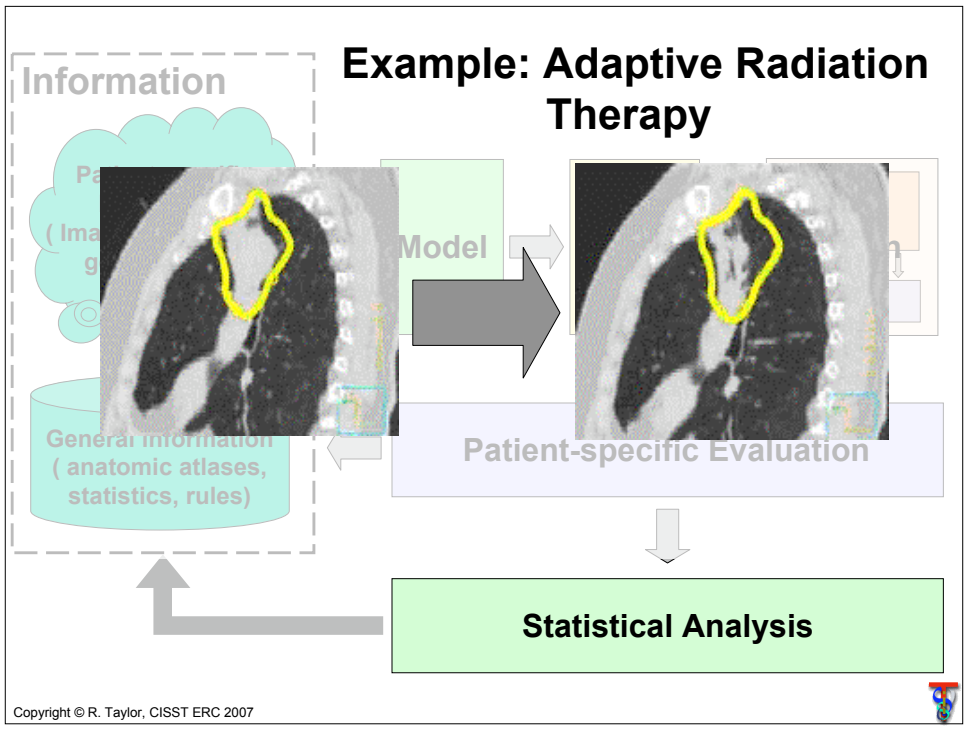


- Prototype, self-contained, very compact imaging and radiation therapy research platform for small animals
- In development as collaboration between JHU Radiation Oncology and CISST ERC

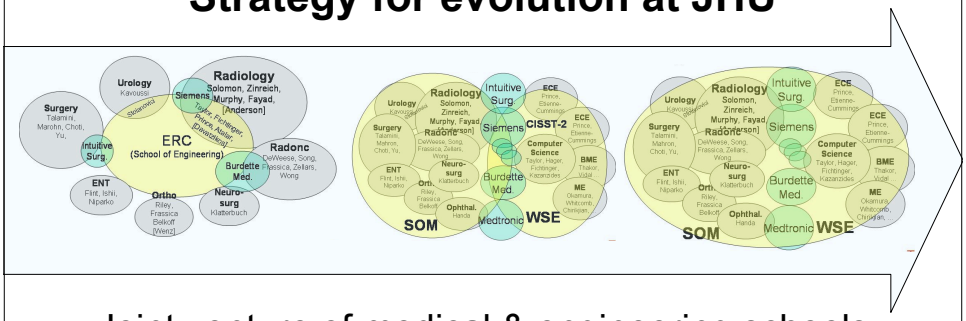





Information
Patient-specific Information (Images, lab results, genetics, etc.)
General information (anatomic atlases, statistics, rules)
Model
Plan
Action
Patient-specific Evaluation
Process Loop
Statistical Analysis
Copyright © R. Taylor, CISST ERC 2007
Figure: R. Taylor


Example: Adaptive Radiation Therapy
Information
Model
Patient-specific Evaluation
Statistical Analysis
Copyright © R. Taylor, CISST ERC 2007

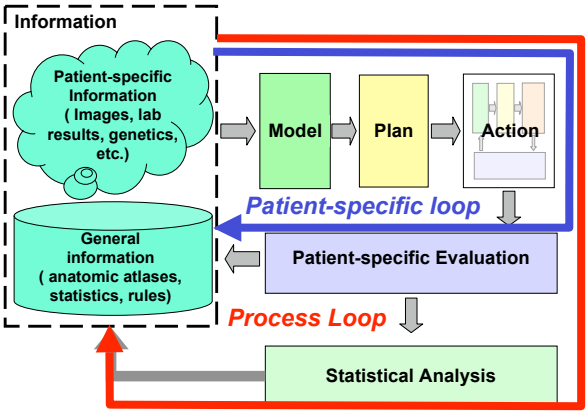
Strategy for evolution at JHU



- 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

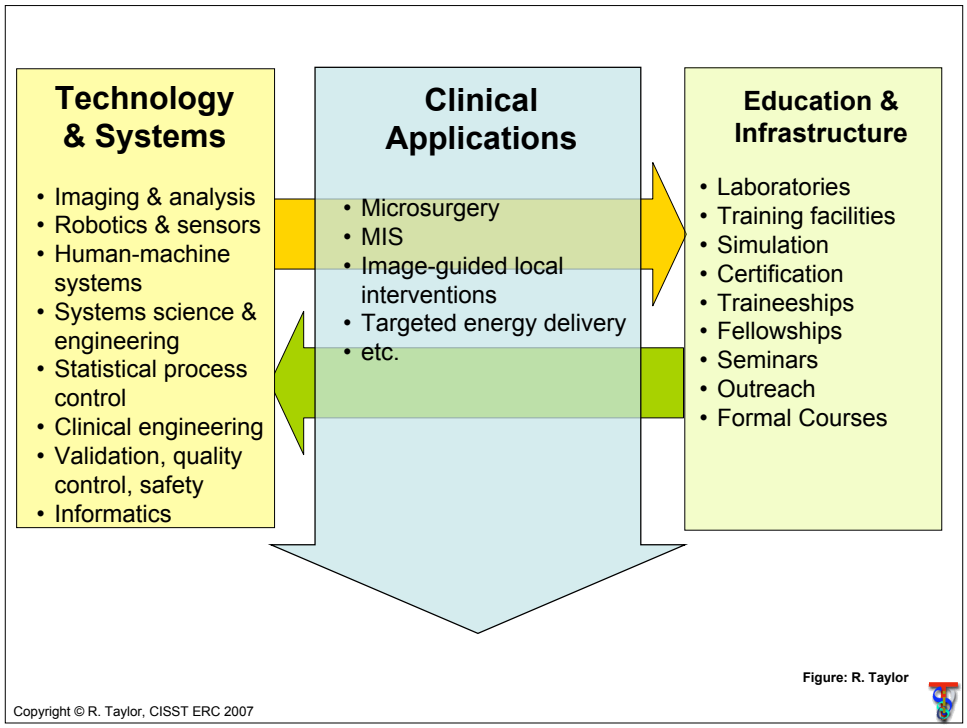
Evolution: Integrating Imaging, Intervention, and Informatics in Medicine (I^4M)

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 say 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

Figure: R. Taylor


Technology & Systems
• Imaging & analysis
• Robotics & sensors
• Human-machine systems
• Systems science & engineering
• Statistical process control
• 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
Figure: R. Taylor
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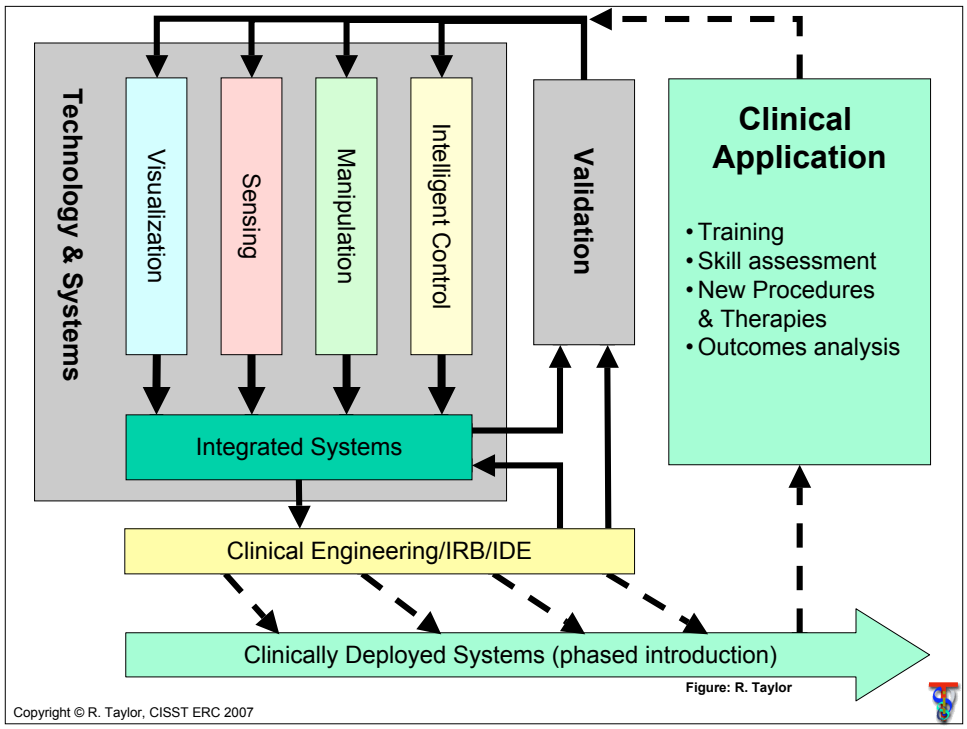

Technology & Systems
Visualization
Sensing
Manipulation
Intelligent Control
Integrated Systems
Validation
Clinical Application
• Training
• Skill assessment
• New Procedures & Therapies
• Outcomes analysis
Clinical Engineering/IRB/IDE
Clinically Deployed Systems (phased introduction)
Figure: R. Taylor
Copyright © R. Taylor, CISST ERC 2007

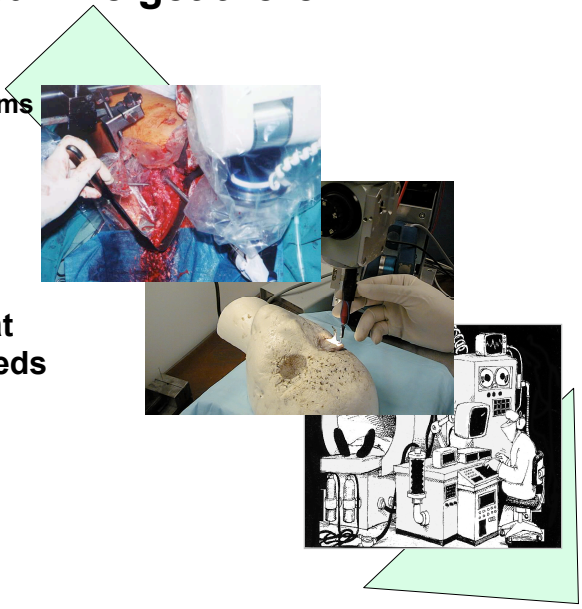
The real bottom line: patient care

- 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

R. Taylor

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!

R. Taylor

What working with surgeons is really like

Discussion

NSF Engineering Research Center
for Computer Integrated Surgical
Systems and Technology

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

rht@jhu.edu

WHITING SCHOOL OF ENGINEERING

THE JOHNS HOPKINS UNIVERSITY