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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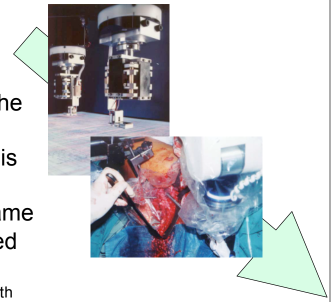
WHITING SCHOOL OF ENGINEERING
THE JOHNS HOPKINS UNIVERSITY

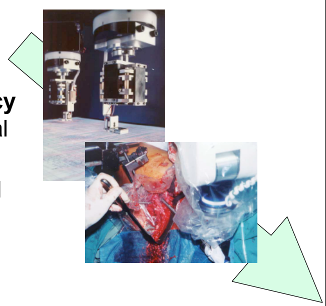
Prediction

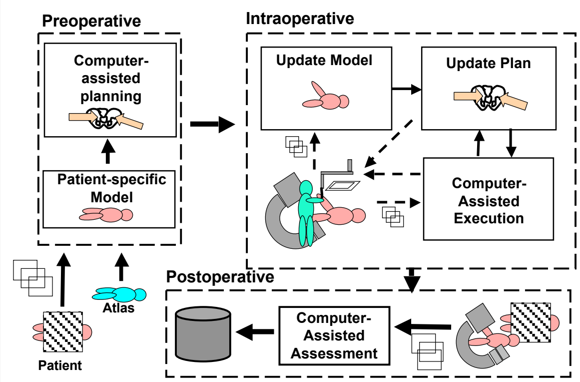
A partnership between human clinicians and computer-based technology will fundamentally change the way surgery and interventional medicine is performed in the 21st Century, in much the same way that computer-based technology changed manufacturing in the 20th Century

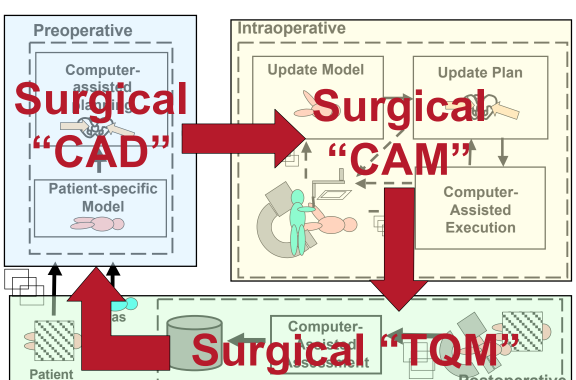


What will drive this change?

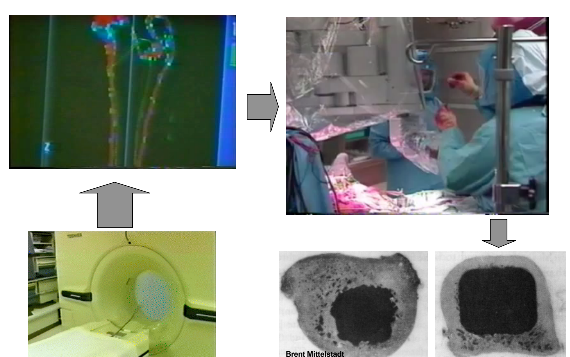
- New capabilities that **transcend human limitations** in surgery
- Increased **consistency and quality** of surgical treatments
- **Better outcomes** and more **cost-effective** processes in surgical practice







Example: Robotic Joint Replacement Surgery

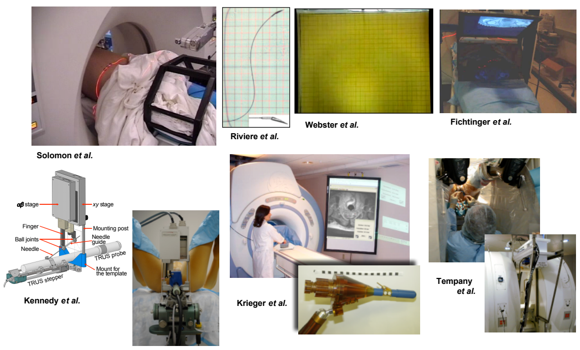


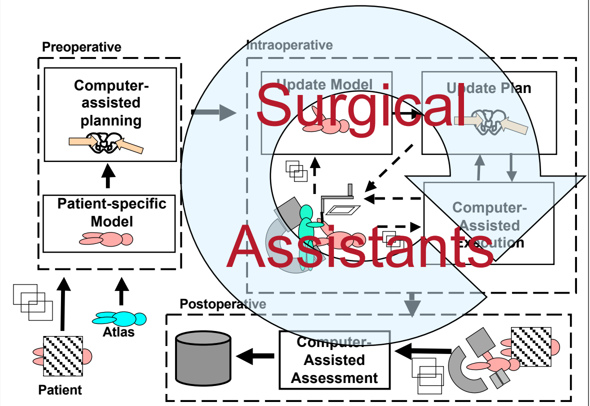
Taylor, Kazanzides, Paul, Mittelstadt, *et al.*

Manual Surgery

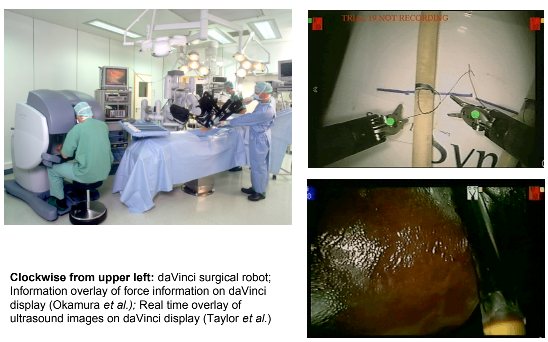
Robotic Surgery

Example: In-imager Needle Placement



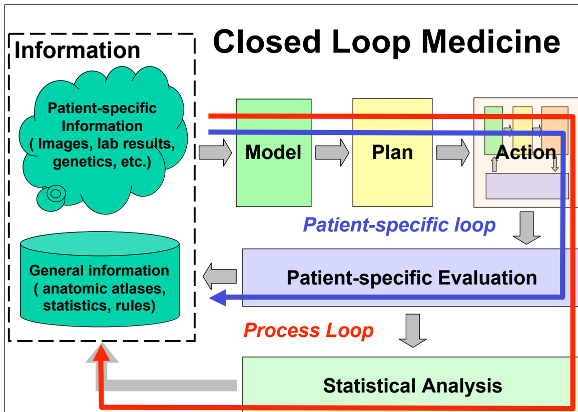


Example: Augmented Reality in Robot-Assisted Surgical Systems



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.*)

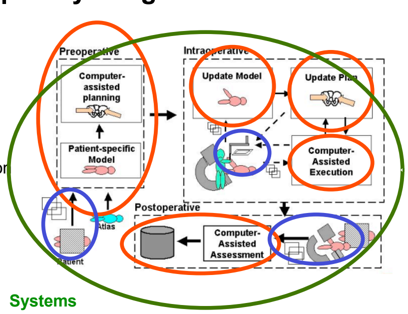
Closed Loop Medicine



Multidisciplinary Integration is Crucial

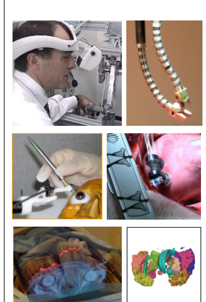
Modeling & analysis
- Segmentation
- Registration
- Atlases
- Optimization
- Visualization
- Task characterization
- *etc.*

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)



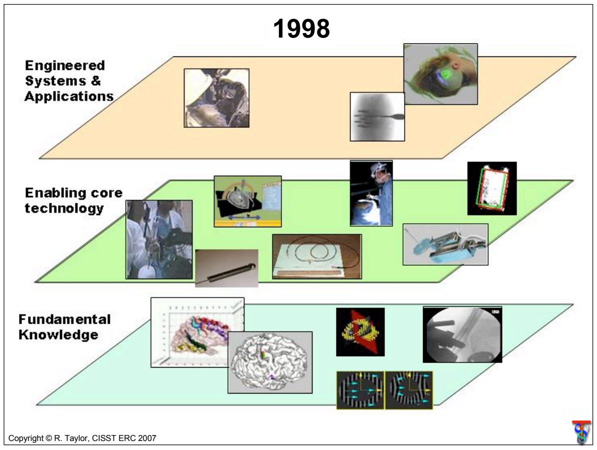
cisstweb.cs.jhu.edu

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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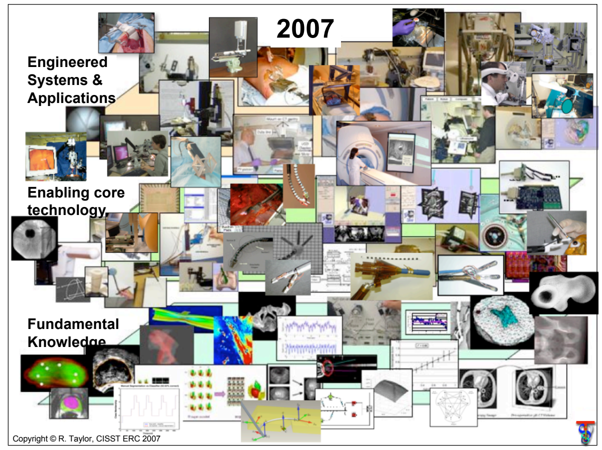
2007
Engineered Systems & Applications
Enabling core technology
Fundamental Knowledge
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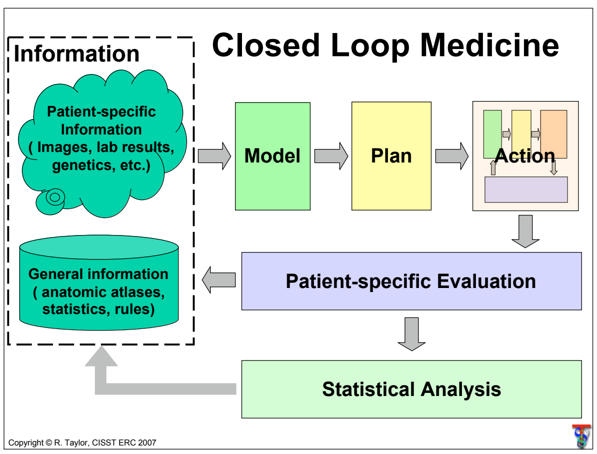
Closed Loop Medicine
Information
Patient-specific Information (Images, lab results, genetics, etc.)
General information (anatomic atlases, statistics, rules)
Model
Plan
Action
Patient-specific Evaluation
Statistical Analysis
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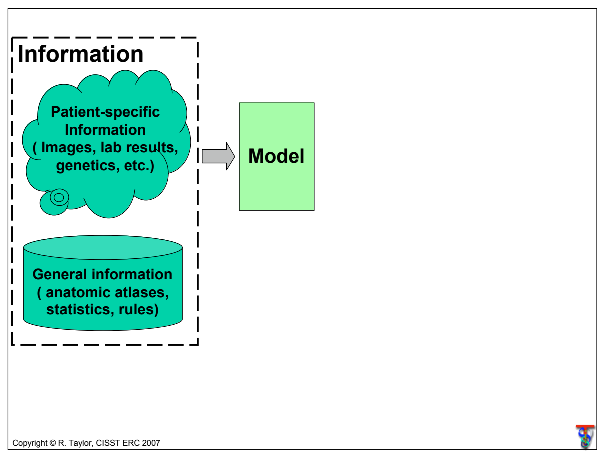
Information
Patient-specific Information (Images, lab results, genetics, etc.)
General information (anatomic atlases, statistics, rules)
Model
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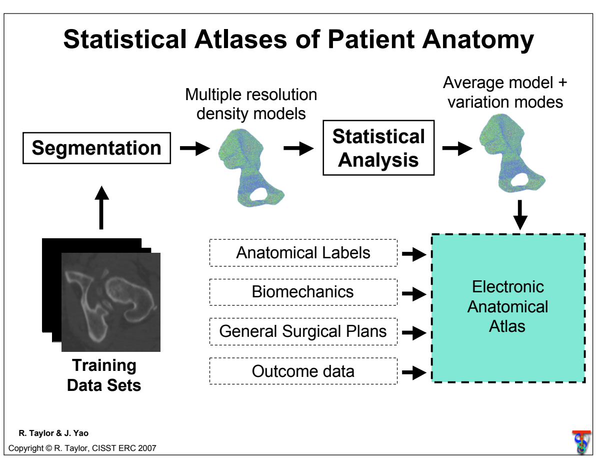
Statistical Atlases of Patient Anatomy
Segmentation
Multiple resolution density models
Statistical Analysis
Average model + variation modes
Training Data Sets
Anatomical Labels
Biomechanics
General Surgical Plans
Outcome data
Electronic Anatomical Atlas
R. Taylor & J. Yao
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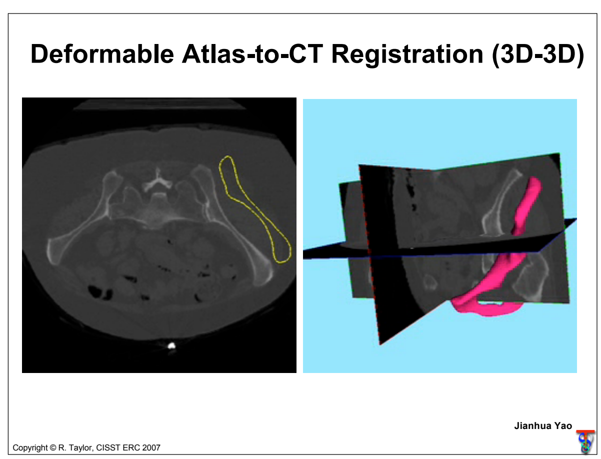
Deformable Atlas-to-CT Registration (3D-3D)
Jianhua Yao
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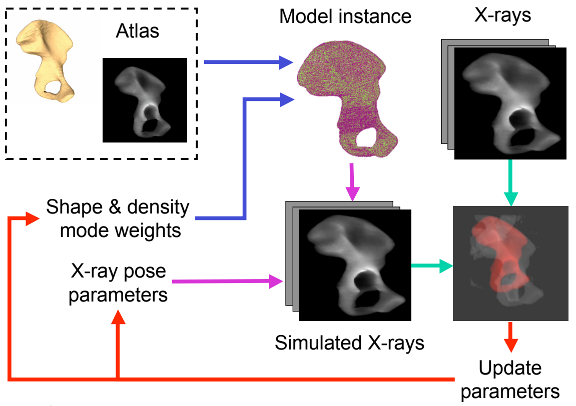
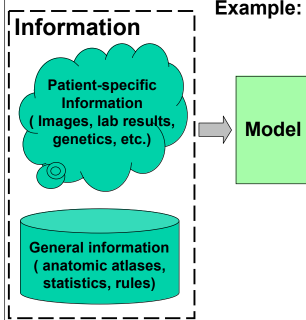
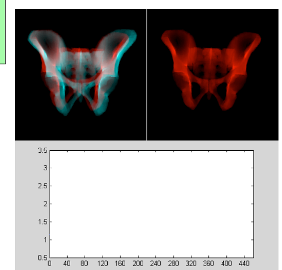


R. Taylor & J. Yao

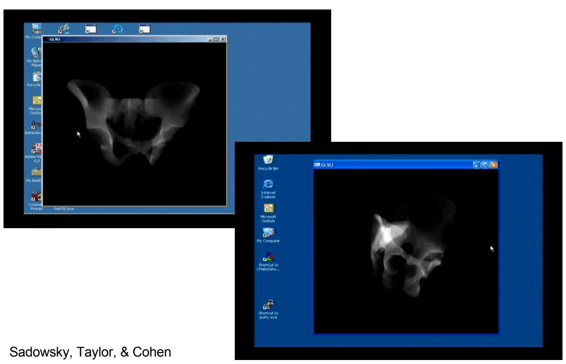
Example: 3D model of patient's pelvis from three 2D x-ray images and prior statistical atlas





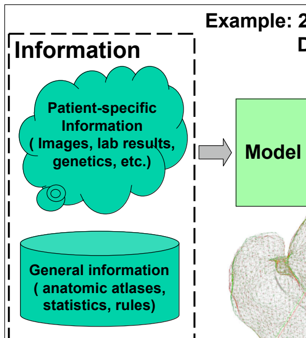
O. Sadowsky, J. Yao, R. Taylor

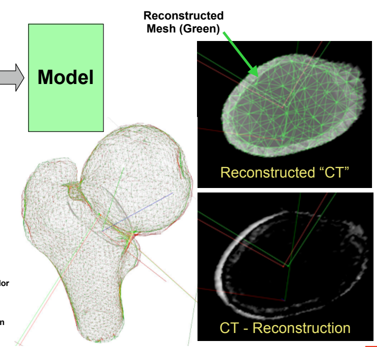
Fast simulated x-rays from deforming model



Sadowsky, Taylor, & Cohen

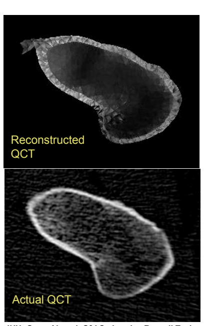
Example: 2D-3D Reconstruction from 3 DEXA Images+Atlas

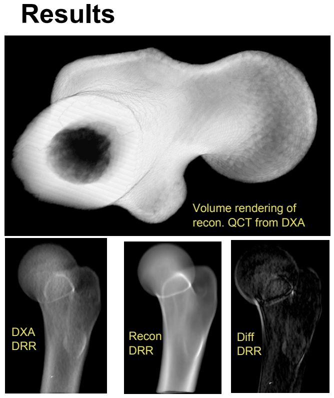




JHU: Omar Ahmad, Ofri Sadowsky, Russell Taylor
U. Erlangen: Klaus Engelke
BIDMC, Boston: Mary Bouxsein
Inst. of Aging Research, Boston: David Karasik
Hologic, Inc.: Krishna Ramamurthi, Kevin Wilson

Results





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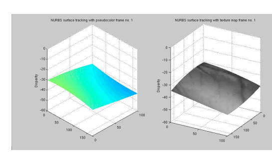
Inst. of Aging Research, Boston: David Karasik
Hologic, Inc.: Krishna Ramamurthi, Kevin Wilson

Real-time Video Techniques

Hager/Thakor/Yuh/Lau (JHU)

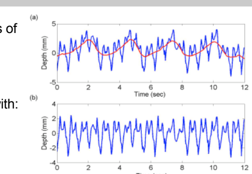


Problem: Construct dynamically tracked models of deformable surfaces

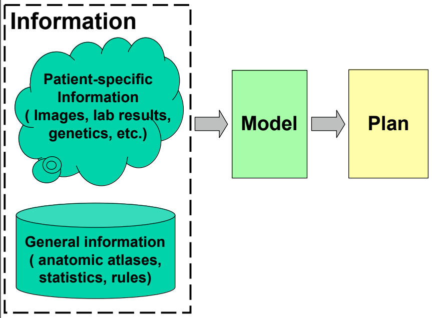
Solution: Optimize a parametric surface from stereo imagery

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

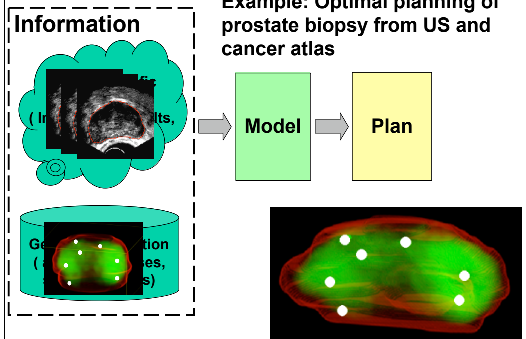
1. Real-time performance
2. Extremely high accuracy (< 1/10 pixel)
3. Generalization to many imaging devices and applications



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



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

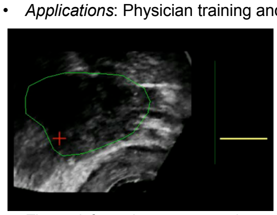


D. Shen, C. Davatzikos, Y. Zhan, C. Tempany, G. Fichtinger, S. Haker, …

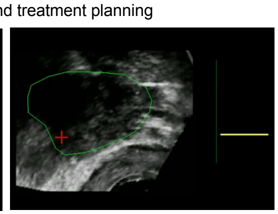
Example: Biomechanical Simulation of Medical Needle Insertion

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

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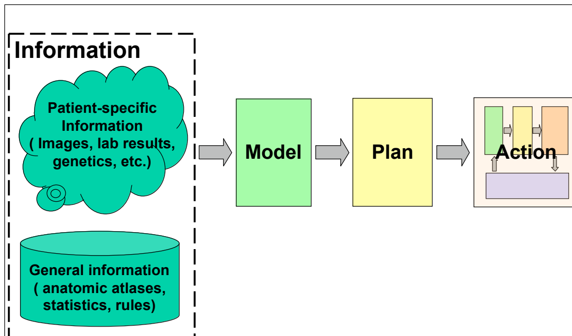
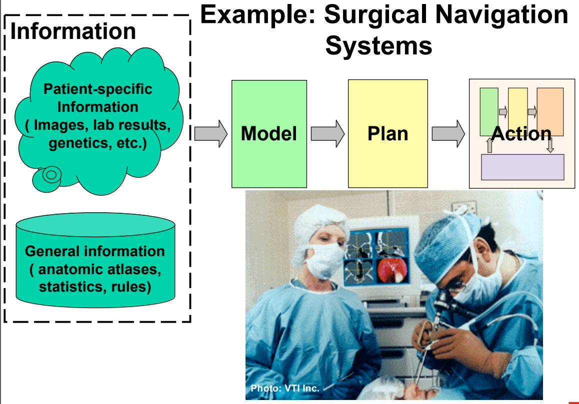
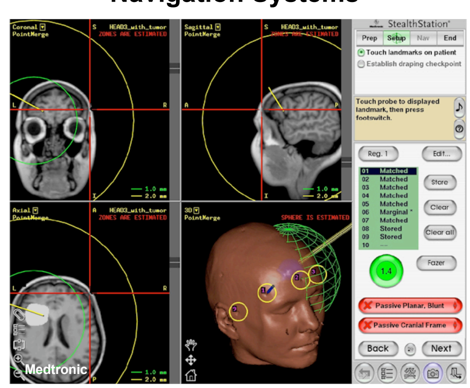


Figure: R. Taylor

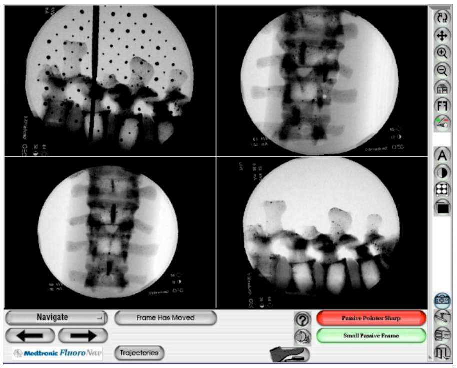
Example: Surgical Navigation Systems

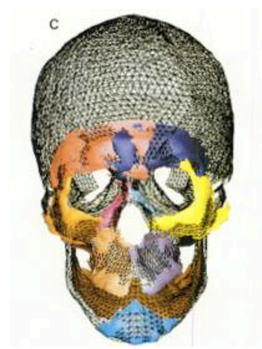


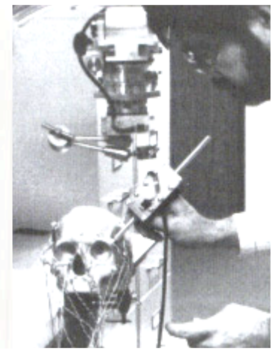
Navigation Systems



Navigation Systems

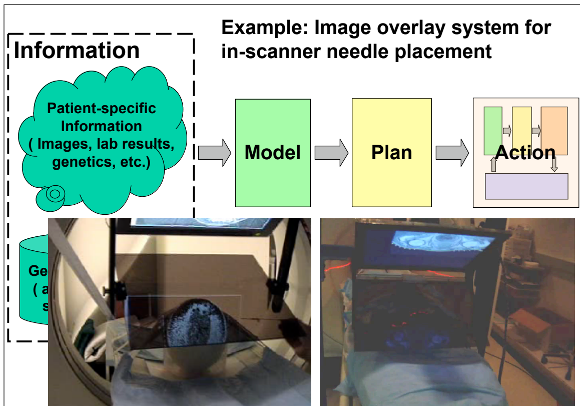






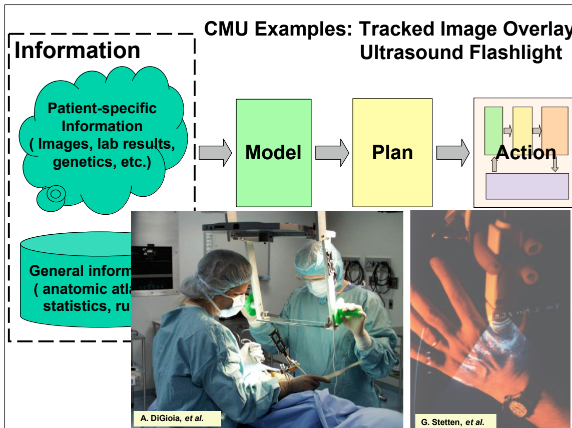
Cutting, Bookstein, Taylor, *et al.*

Example: Image overlay system for in-scanner needle placement



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

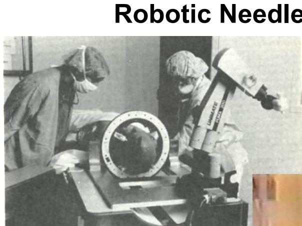
CMU Examples: Tracked Image Overlay Ultrasound Flashlight



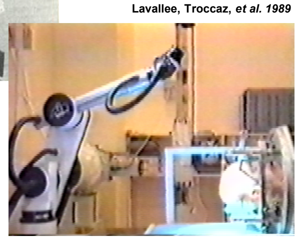
A. DiGioia, *et al.*

G. Stetten, *et al.*

Robotic Needle Guidance

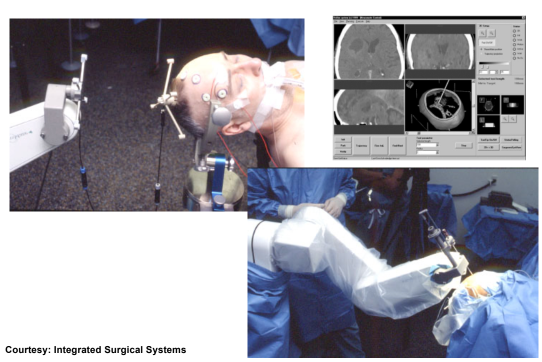


Kwoh, *et al.* 1988

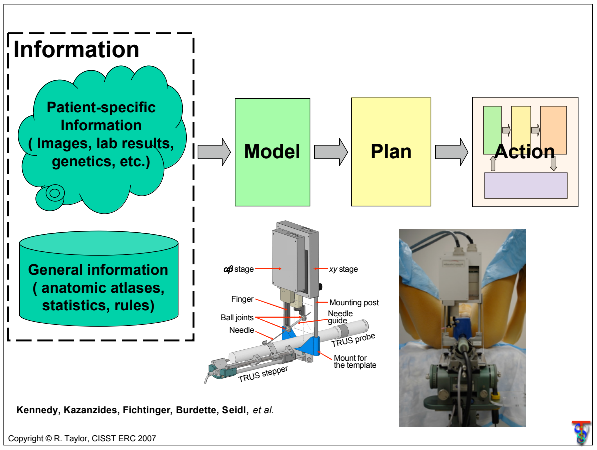


Lavallee, Troccaz, *et al.* 1989

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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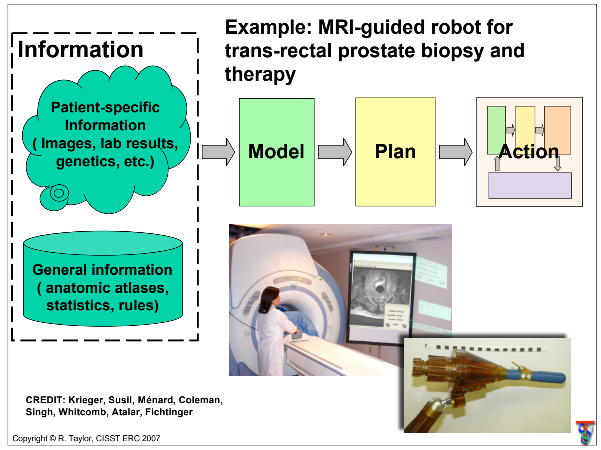
Example: MRI-guided robot for trans-rectal prostate biopsy and therapy
Information
Patient-specific Information (Images, lab results, genetics, etc.)
General information (anatomic atlases, statistics, rules)
Model
Plan
Action
CREDIT: Krieger, Susil, Ménard, Coleman, Singh, Whitcomb, Atalar, Fichtinger
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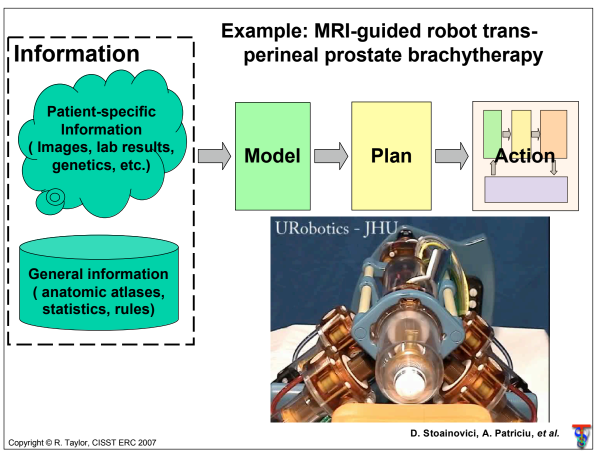
Example: MRI-guided robot trans-perineal prostate brachytherapy
Information
Patient-specific Information (Images, lab results, genetics, etc.)
General information (anatomic atlases, statistics, rules)
Model
Plan
Action
URobotics - JHU
D. Stoainovici, A. Patriciu, et al.
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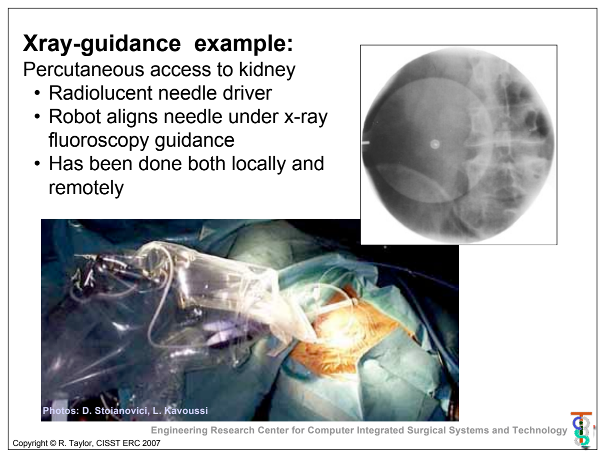
Xray-guidance example:
Percutaneous access to kidney
• Radiolucent needle driver
• Robot aligns needle under x-ray fluoroscopy guidance
• Has been done both locally and remotely
Photos: D. Stoianovici, L. Kavoussi
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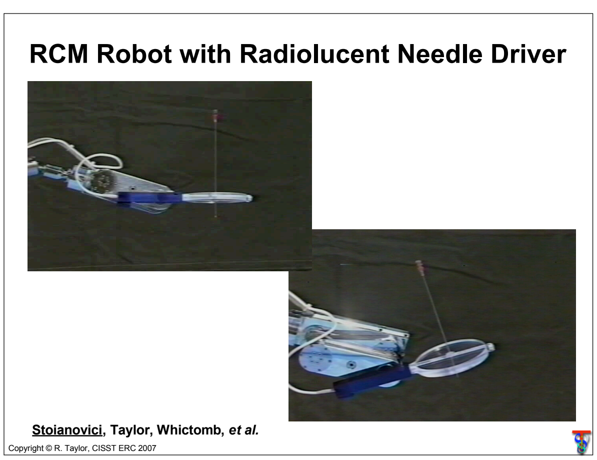
RCM Robot with Radiolucent Needle Driver
Stoianovici, Taylor, Whictomb, et al.
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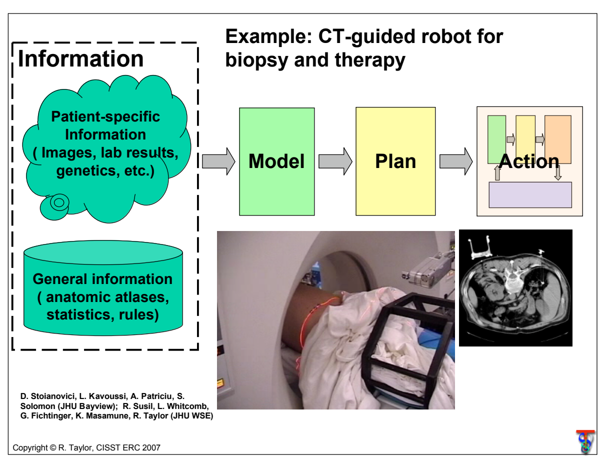
Example: CT-guided robot for biopsy and therapy
Information
Patient-specific Information (Images, lab results, genetics, etc.)
General information (anatomic atlases, statistics, rules)
Model
Plan
Action
D. Stoianovici, L. Kavoussi, A. Patriciu, S. Solomon (JHU Bayview); R. Susil, L. Whitcomb, G. Fichtinger, K. Masamune, R. Taylor (JHU WSE)
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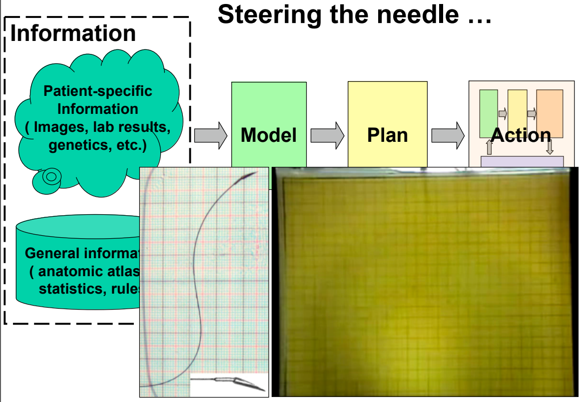
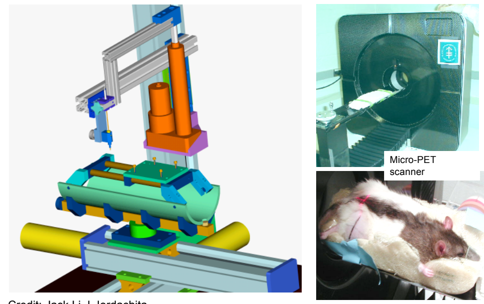
Steering the needle …



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

Robotic Needle Placement in Rodents

P. Kazanzides, G. Fichtinger, C. Ling

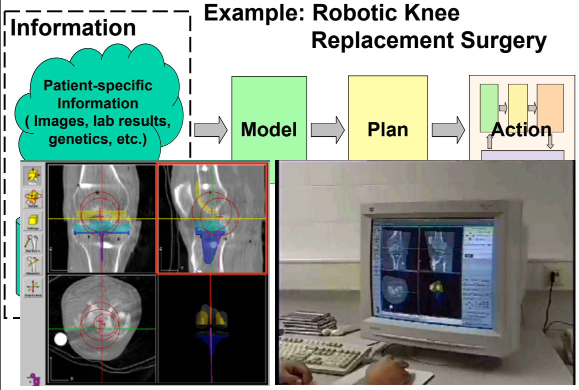


Credit: Jack Li, I. Iordachita

Courtesy of MSKCC

Research contract from Sloan Kettering

Example: Robotic Knee Replacement Surgery

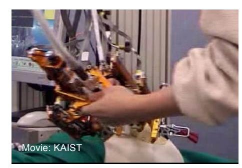


Photos: Integrated Surgical Systems

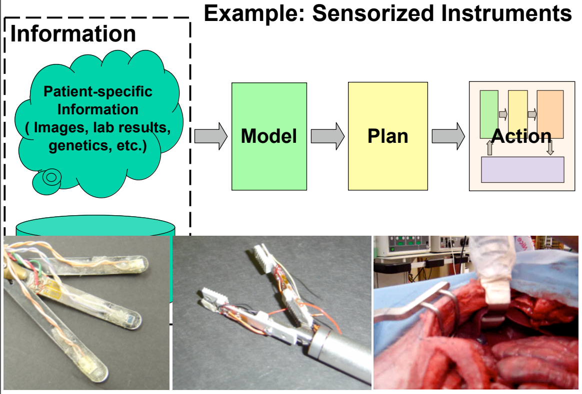
Figure: R. Taylor

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

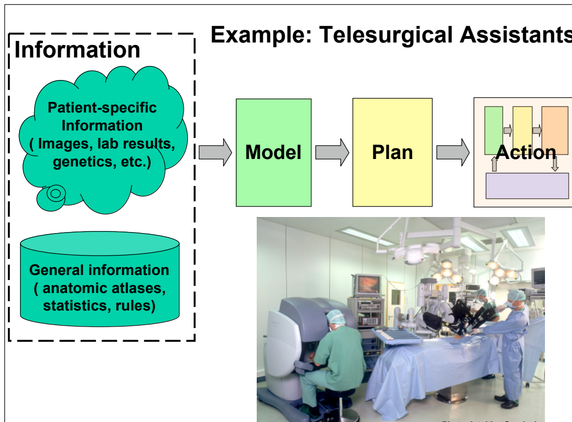
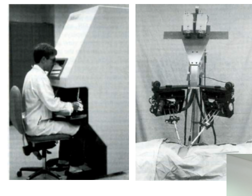


Photo: Intuitive Surgical

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

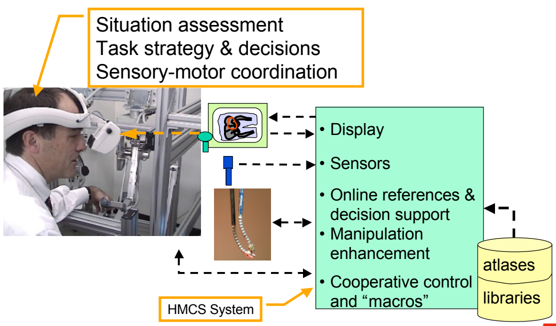
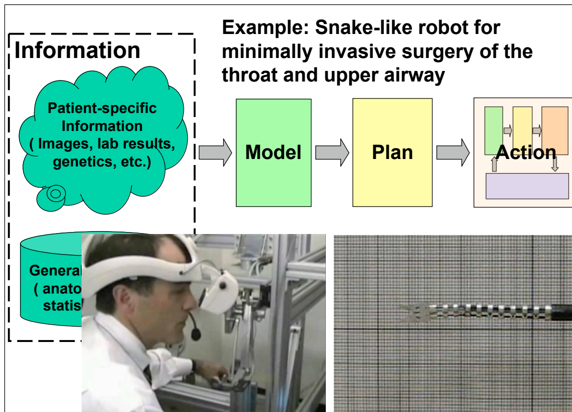


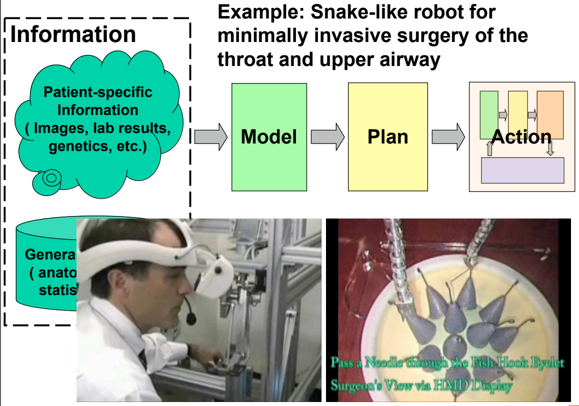
Figure: R. Taylor

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



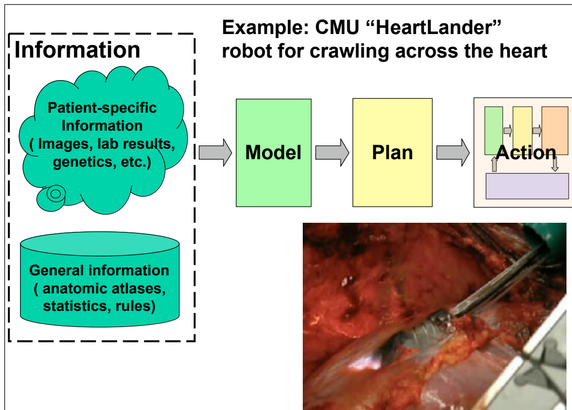
Simaan, Taylor, Flint, Kapoor, Wei , Xu

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

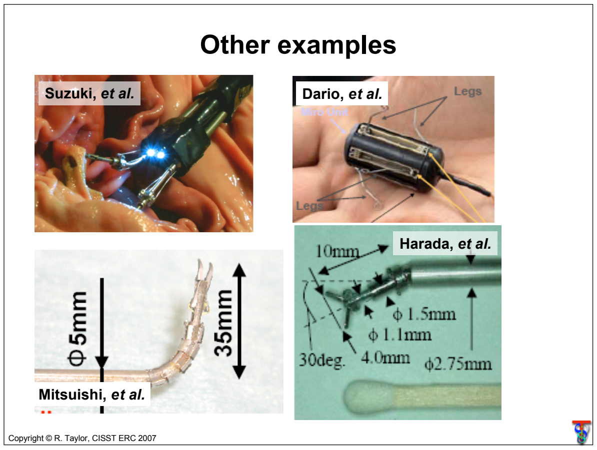


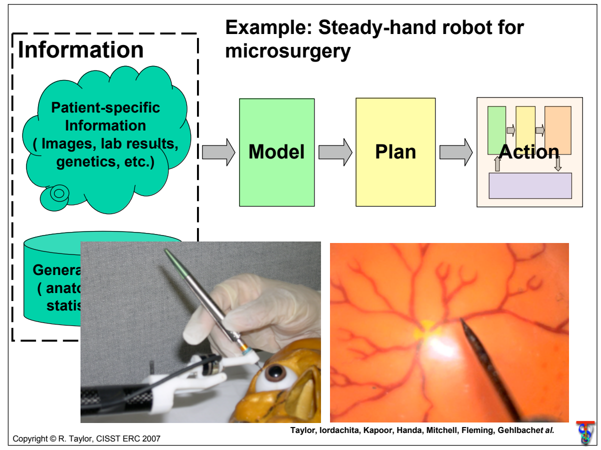
Simaan, Taylor, Flint, Kapoor, Wei , Xu

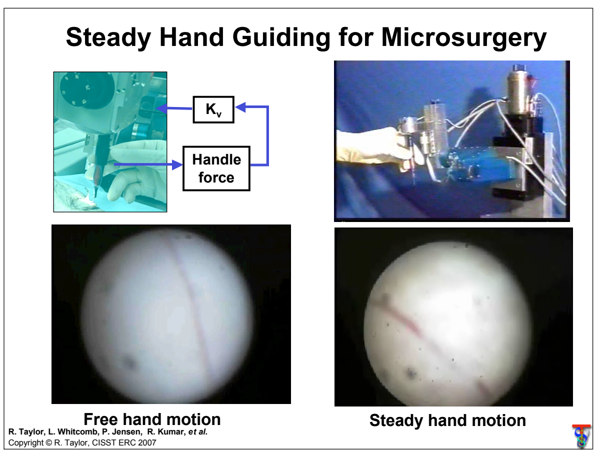
Example: CMU “HeartLander” robot for crawling across the heart

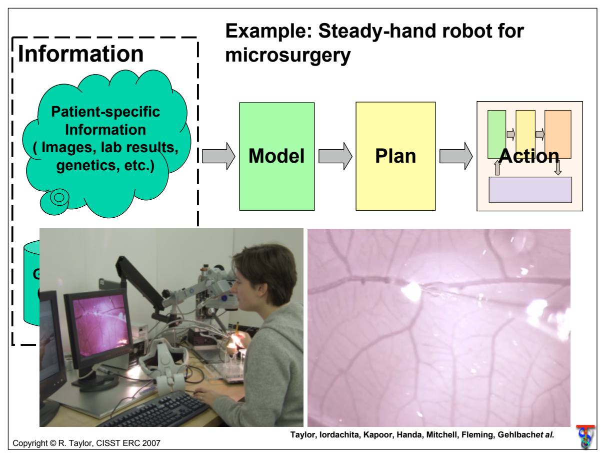


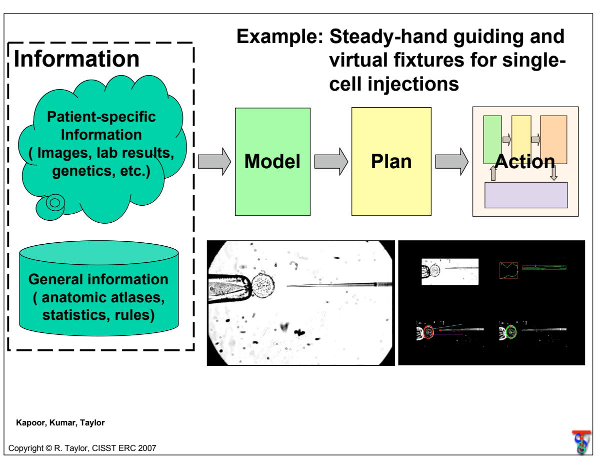
Cameron Riviere, CMU

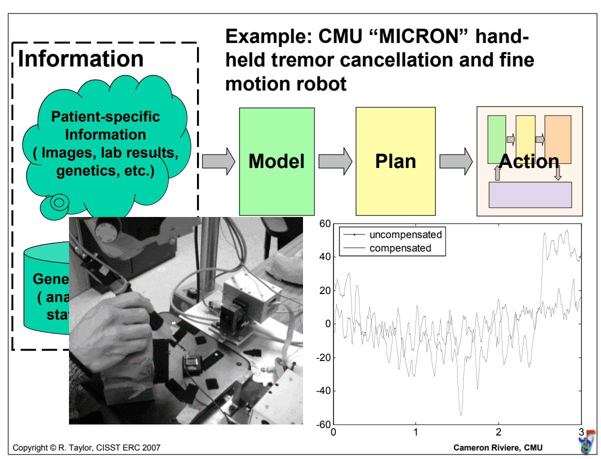

Other examples
Suzuki, et al.
Dario, et al.
Legs
Legs
Harada, et al.
10mm
ϕ 1.5mm
ϕ 1.1mm
30deg.
4.0mm
ϕ2.75mm
Φ5mm
35mm
Mitsuishi, et al.
Copyright © R. Taylor, CISST ERC 2007


Information
Example: Steady-hand robot for microsurgery
Patient-specific Information (Images, lab results, genetics, etc.)
Model
Plan
Action
Taylor, Iordachita, Kapoor, Handa, Mitchell, Fleming, Gehlbach et al.
Copyright © R. Taylor, CISST ERC 2007

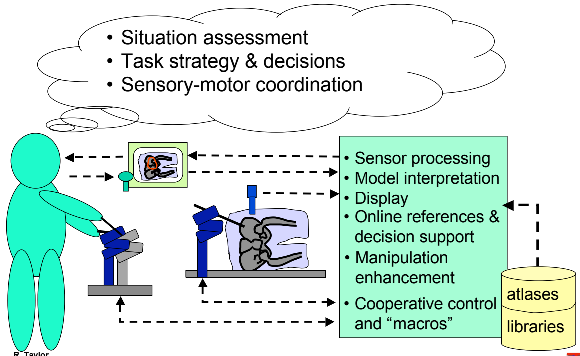

Steady Hand Guiding for Microsurgery
Kv
Handle force
Free hand motion
Steady hand motion
R. Taylor, L. Whitcomb, P. Jensen, R. Kumar, et al.
Copyright © R. Taylor, CISST ERC 2007


Information
Example: Steady-hand robot for microsurgery
Patient-specific Information (Images, lab results, genetics, etc.)
Model
Plan
Action
Taylor, Iordachita, Kapoor, Handa, Mitchell, Fleming, Gehlbach et al.
Copyright © R. Taylor, CISST ERC 2007


Information
Example: Steady-hand guiding and virtual fixtures for single-cell injections
Patient-specific Information (Images, lab results, genetics, etc.)
General information (anatomic atlases, statistics, rules)
Model
Plan
Action
Kapoor, Kumar, Taylor
Copyright © R. Taylor, CISST ERC 2007

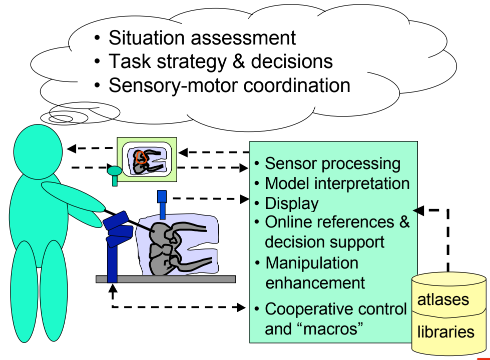

Information
Example: CMU "MICRON" hand-held tremor cancellation and fine motion robot
Patient-specific Information (Images, lab results, genetics, etc.)
Model
Plan
Action
uncompensated
compensated
60
40
20
0
-20
-40
-60
0
1
2
3
Cameron Riviere, CMU
Copyright © R. Taylor, CISST ERC 2007

Evolution to human-machine partnership



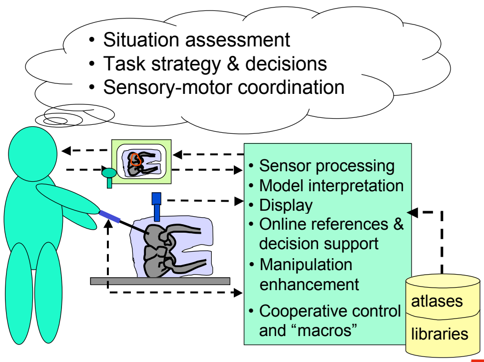
R. Taylor

Evolution to human-machine partnership



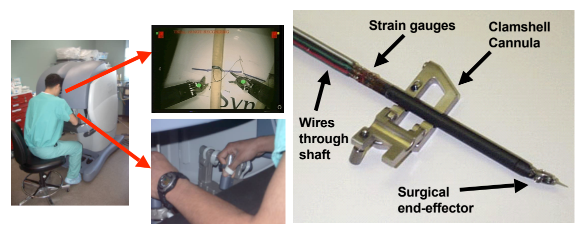
R. Taylor

Evolution to human-machine partnership



R. Taylor

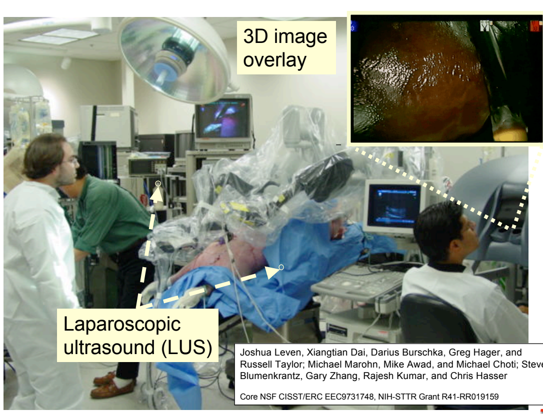
Dynamic Augmented Reality for Sensory Substitution in Robot-Assisted Surgical Systems



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

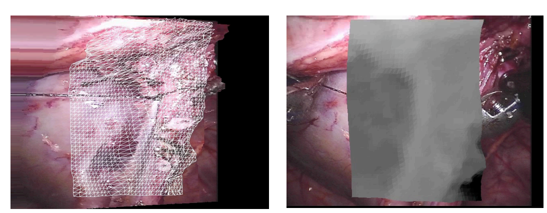
A. Okamura, T. Akinbiyi, *et al.*



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

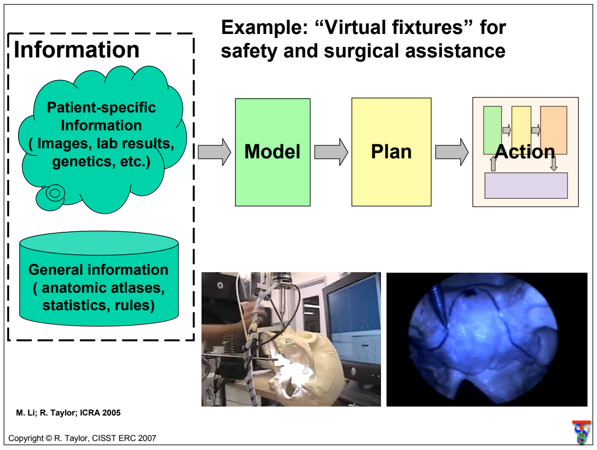
Core NSF CISST/ERC EEC9731748, NIH-STTR Grant R41-RR019159

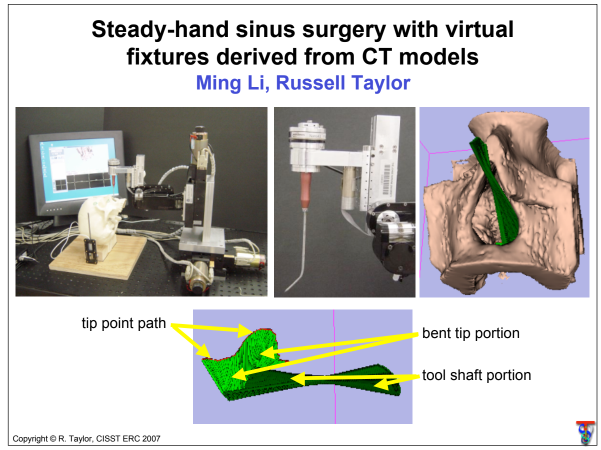
Real Time Deformable Registration and Overlay

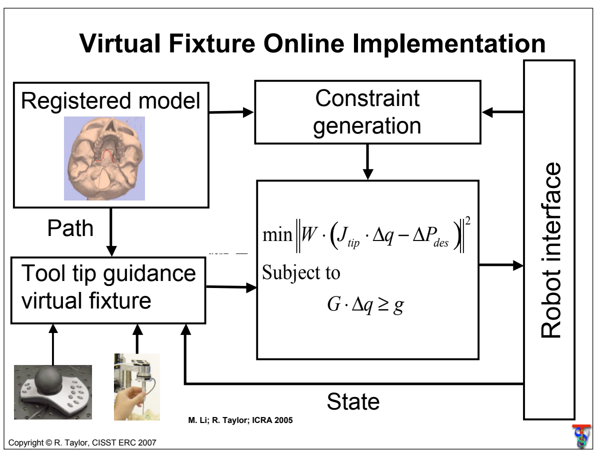


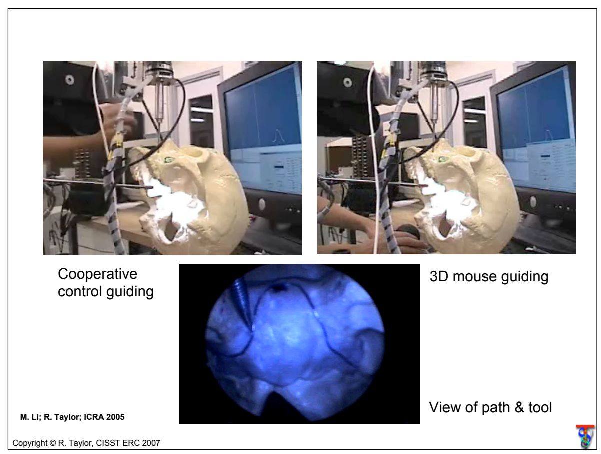
Final registration error of < 1mm except for the area where the tool enters the image

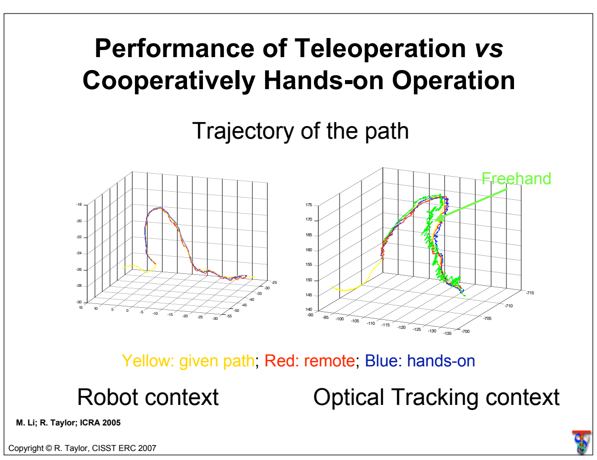
Vagvolgyi, Hager, *et al.*

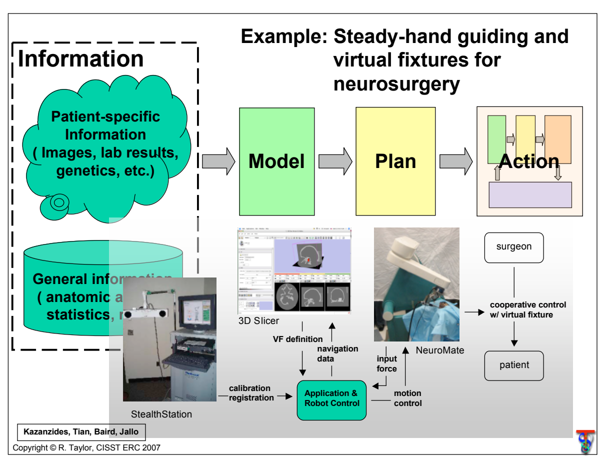

Example: "Virtual fixtures" for safety and surgical assistance
Information
Patient-specific Information (Images, lab results, genetics, etc.)
General information (anatomic atlases, statistics, rules)
Model
Plan
Action
M. Li; R. Taylor; ICRA 2005
Copyright © R. Taylor, CISST ERC 2007

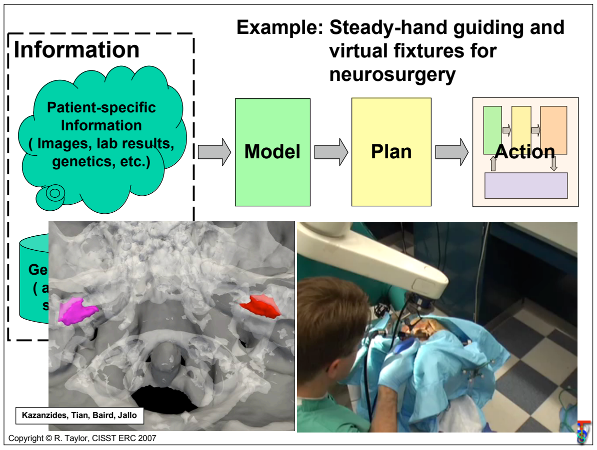

Steady-hand sinus surgery with virtual fixtures derived from CT models
Ming Li, Russell Taylor
tip point path
bent tip portion
tool shaft portion
Copyright © R. Taylor, CISST ERC 2007

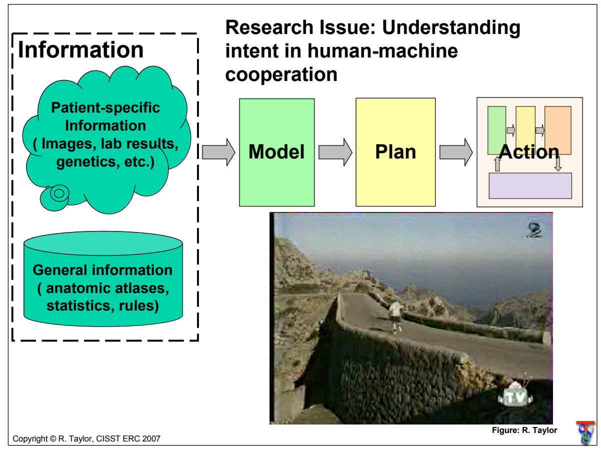

Virtual Fixture Online Implementation
Registered model
Constraint generation
Path
Tool tip guidance virtual fixture
$\min \left\| W \cdot (J_{tip} \cdot \Delta q - \Delta P_{des}) \right\|^2$
Subject to
$G \cdot \Delta q \geq g$
Robot interface
State
M. Li; R. Taylor; ICRA 2005
Copyright © R. Taylor, CISST ERC 2007

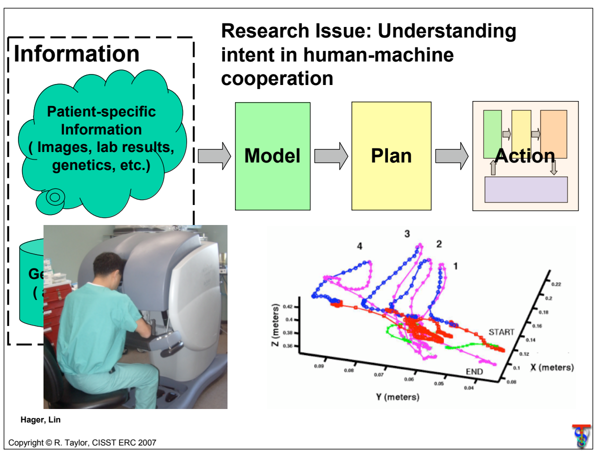

Cooperative control guiding
3D mouse guiding
View of path & tool
M. Li; R. Taylor; ICRA 2005
Copyright © R. Taylor, CISST ERC 2007

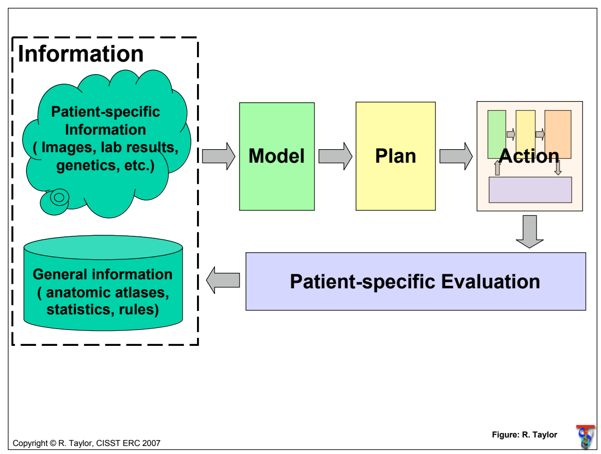

Performance of Teleoperation vs Cooperatively Hands-on Operation
Trajectory of the path
Freehand
Yellow: given path; Red: remote; Blue: hands-on
Robot context
Optical Tracking context
M. Li; R. Taylor; ICRA 2005
Copyright © R. Taylor, CISST ERC 2007

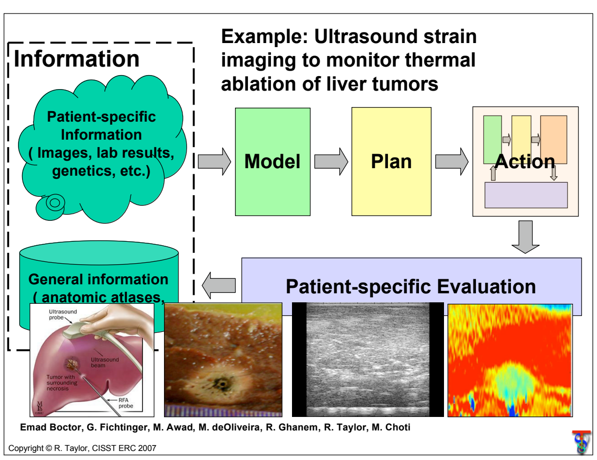

Example: Steady-hand guiding and virtual fixtures for neurosurgery
Information
Patient-specific Information (Images, lab results, genetics, etc.)
Model
Plan
Action
3D Slicer
VF definition
navigation data
input force
NeuroMate
surgeon
cooperative control w/ virtual fixture
patient
calibration registration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

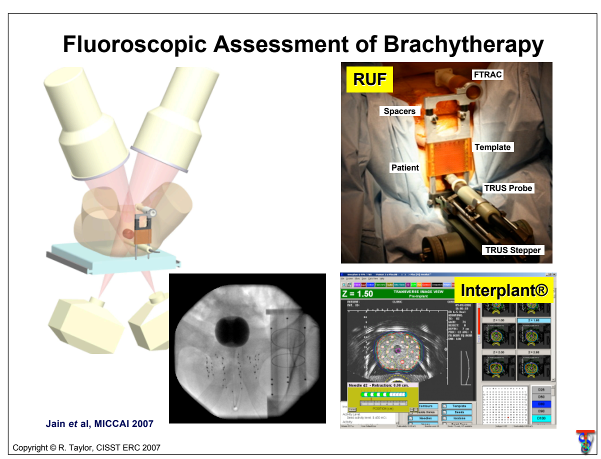

Example: Steady-hand guiding and virtual fixtures for neurosurgery
Information
Patient-specific Information (Images, lab results, genetics, etc.)
Model
Plan
Action
Kazanzides, Tian, Baird, Jallo
Copyright © R. Taylor, CISST ERC 2007

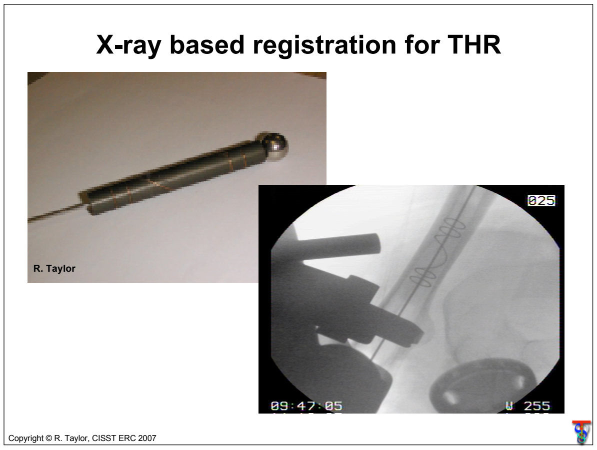

Research Issue: Understanding intent in human-machine cooperation
Information
Patient-specific Information (Images, lab results, genetics, etc.)
General information (anatomic atlases, statistics, rules)
Model
Plan
Action
Figure: R. Taylor
Copyright © R. Taylor, CISST ERC 2007

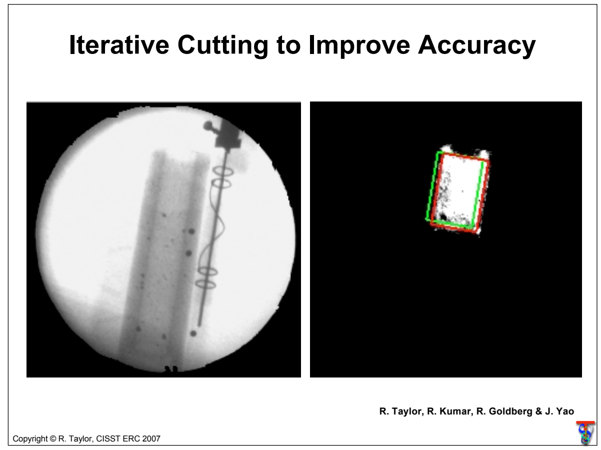

Research Issue: Understanding intent in human-machine cooperation
Information
Patient-specific Information (Images, lab results, genetics, etc.)
Model
Plan
Action
START
END
Z (meters)
Y (meters)
X (meters)
Hager, Lin
Copyright © R. Taylor, CISST ERC 2007

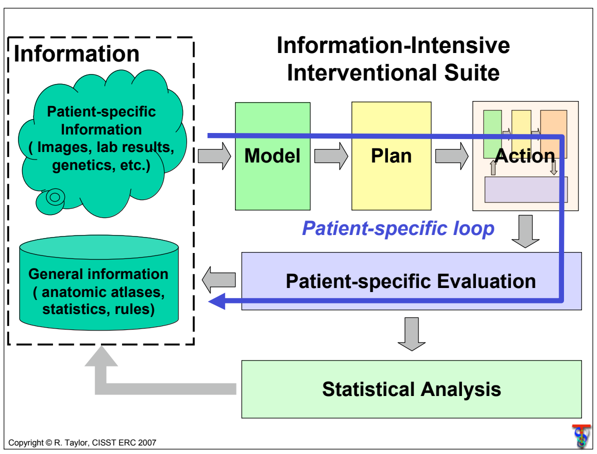

Information
Patient-specific Information (Images, lab results, genetics, etc.)
General information (anatomic atlases, statistics, rules)
Model
Plan
Action
Patient-specific Evaluation
Figure: R. Taylor
Copyright © R. Taylor, CISST ERC 2007

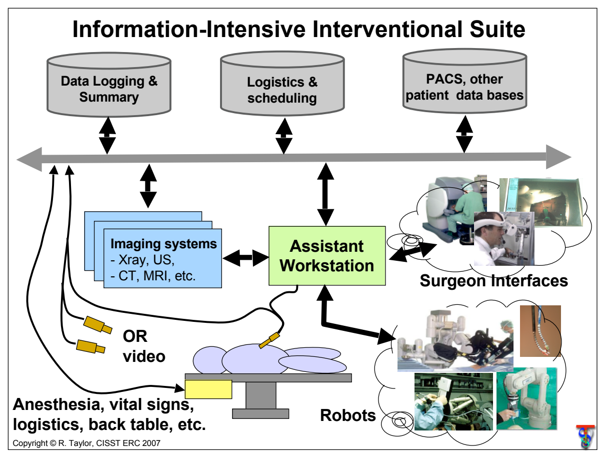

Example: Ultrasound strain imaging to monitor thermal ablation of liver tumors
Information
Patient-specific Information (Images, lab results, genetics, etc.)
General information (anatomic atlases,
Model
Plan
Action
Patient-specific Evaluation
Emad Boctor, G. Fichtinger, M. Awad, M. deOliveira, R. Ghanem, R. Taylor, M. Choti
Copyright © R. Taylor, CISST ERC 2007

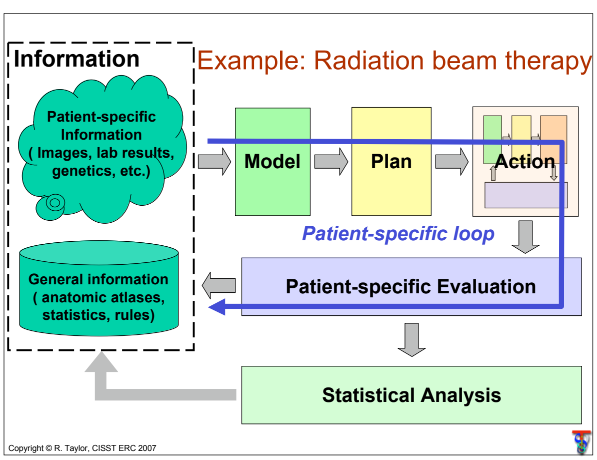

Fluoroscopic Assessment of Brachytherapy
RUF
FTRAC
Spacers
Template
Patient
TRUS Probe
TRUS Stepper
Interplant®
Jain et al, MICCAI 2007
Copyright © R. Taylor, CISST ERC 2007

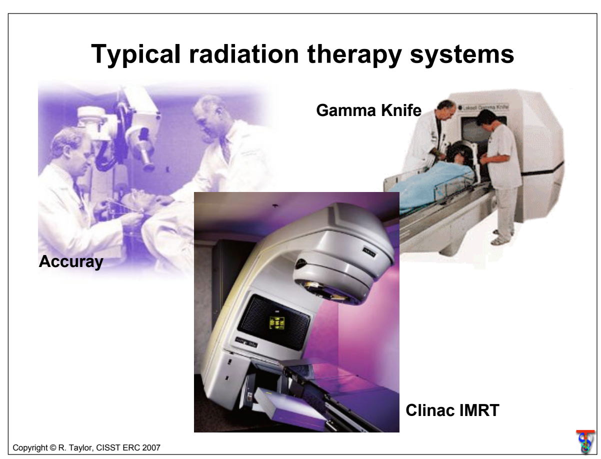

X-ray based registration for THR
R. Taylor
Copyright © R. Taylor, CISST ERC 2007


Iterative Cutting to Improve Accuracy
R. Taylor, R. Kumar, R. Goldberg & J. Yao
Copyright © R. Taylor, CISST ERC 2007


Information
Information-Intensive Interventional Suite
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


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
Copyright © R. Taylor, CISST ERC 2007


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
Copyright © R. Taylor, CISST ERC 2007

External Beam Radiotherapy

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

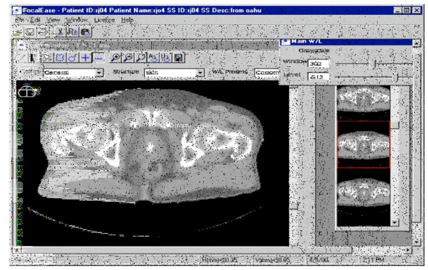
Planning CT

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)

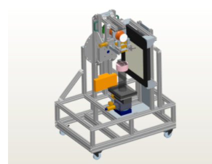
US Based Prostate Localization?

- Poor image quality
- Operator dependent
- Prostate bounces

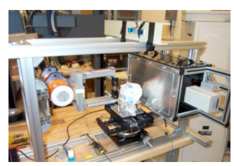
CREDIT: Resonant, RESTITU™ platform

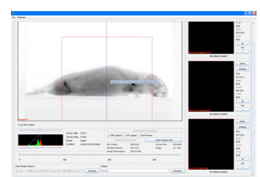
Small Animal Radiation Research Platform

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





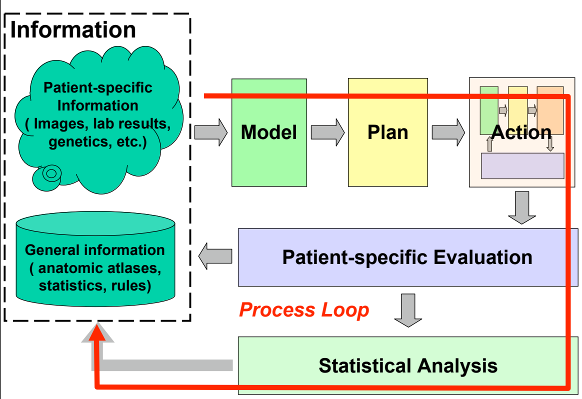
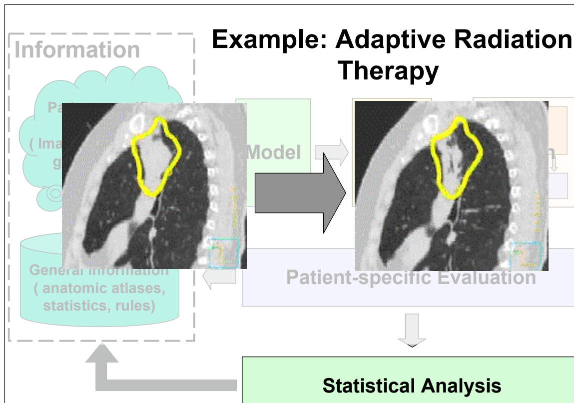
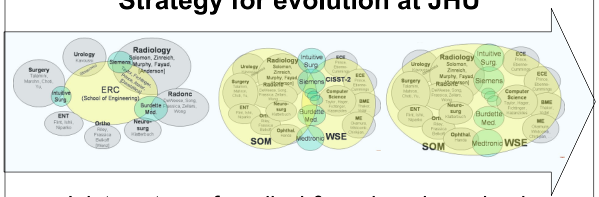


Figure: R. Taylor

Example: Adaptive Radiation Therapy



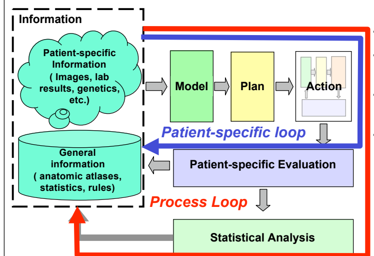
Strategy for evolution at JHU



- 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 (I⁴M)

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

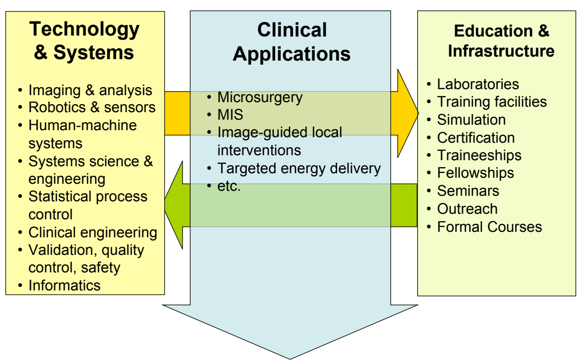


Figure: R. Taylor

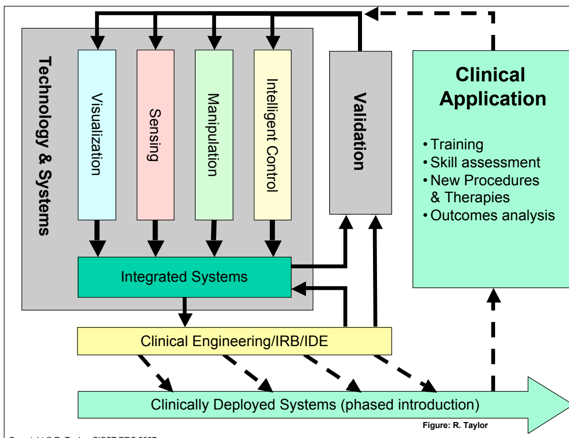


Figure: R. Taylor

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

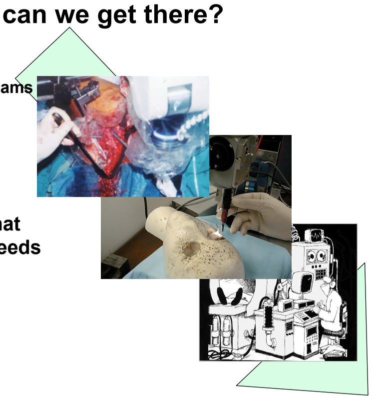
How can we get there?

Strong and committed teams
- Surgeons
- Engineers
- Industry

Focus on systems that address important needs

Rapid iteration with measurable goals

Have fun!



R. Taylor

What research 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