Medical Robots and their Control Paradigms

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My Background

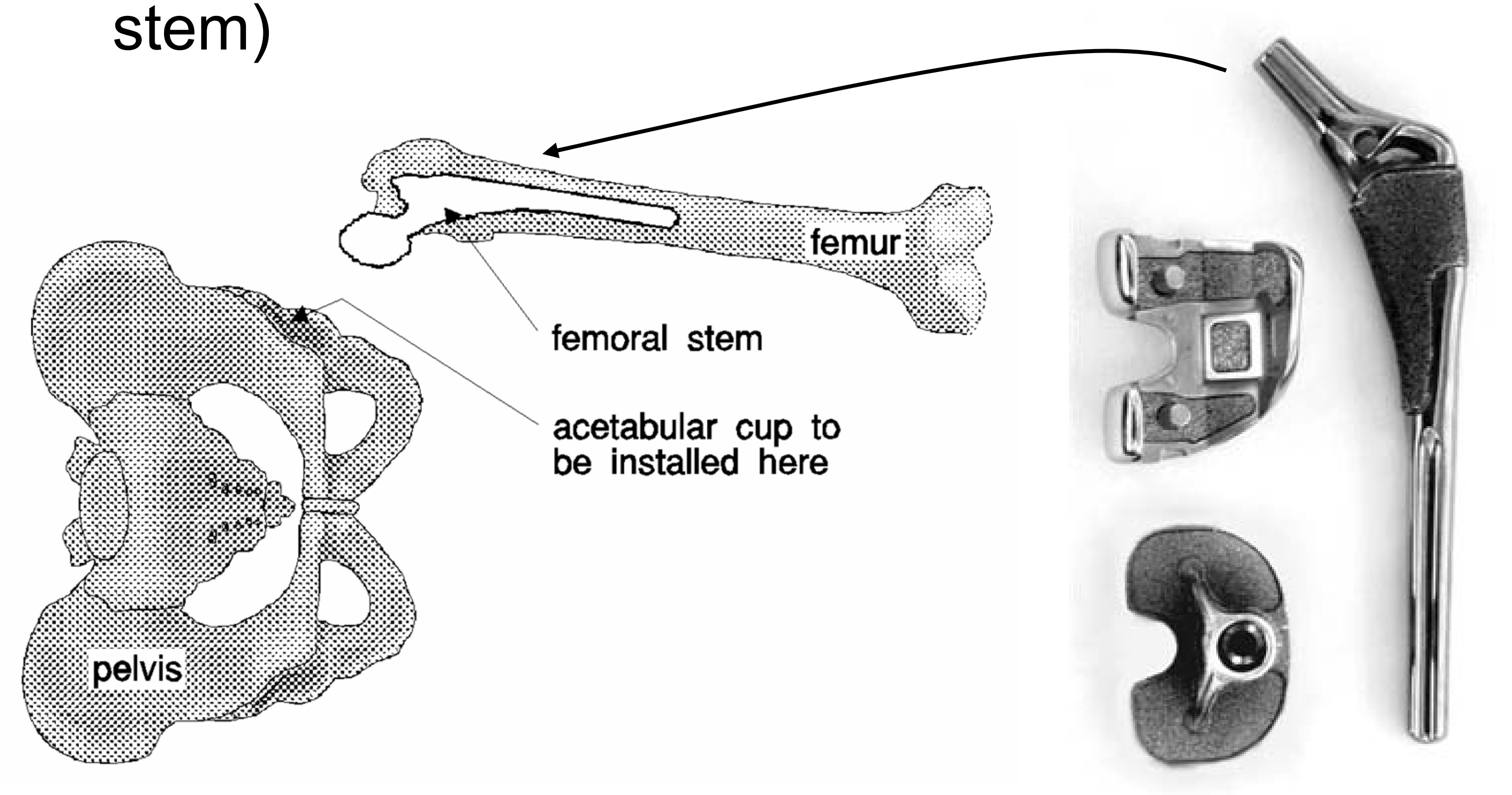
- 1983-1988 Ph.D. EE (Robotics), Brown University
  - Thesis: Multiprocessor Control of Robotic Manipulators
- 1989-1990 Postdoctoral researcher at IBM
  - Medical robotics (ROBODOC)
- 1990-2002 Co-Founder of Integrated Surgical Systems
  - Director of Robotics and Software
  - Commercial development of ROBODOC® System
  - Sales in Europe (CE Mark) and Asia
  - Clinical trials in U.S. and Japan
- 2002-present Research faculty at JHU
  - Research in use of robotics for neurosurgery, cancer research and therapy, telesurgery, microsurgery, …

Outline

- Overview of ROBODOC System
- Medical robotics at JHU
- What are the control challenges?
- Force control in ROBODOC
- Cooperative Control with Virtual Fixtures
- Constrained optimization formulation
- Conclusions

ROBODOC® System

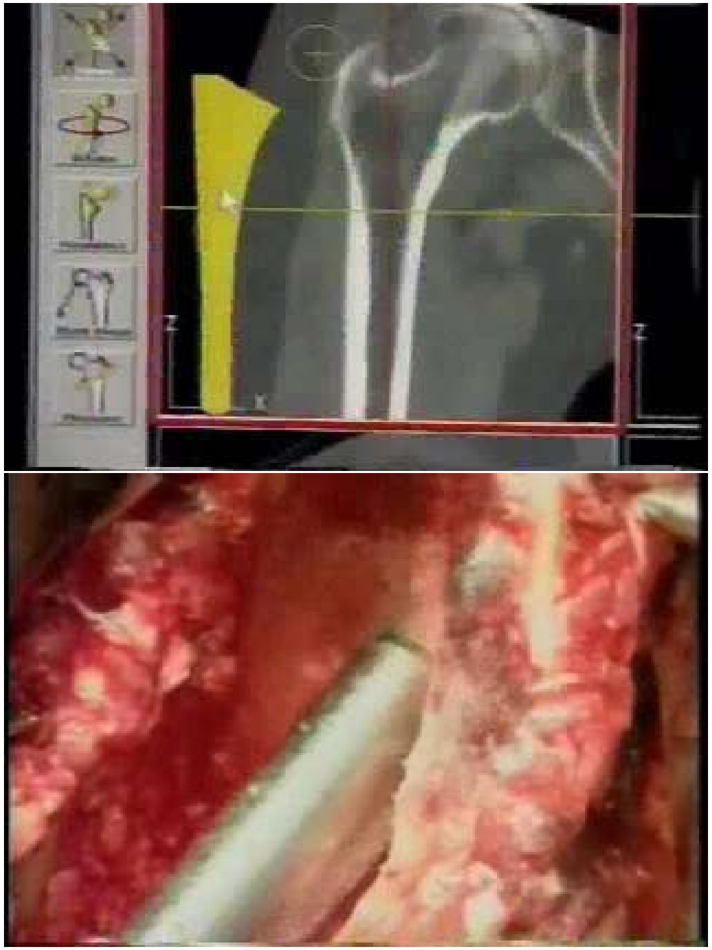
- Initially developed to assist with Total Hip Replacement (THR) surgery
  - machine femur for cementless prosthesis (femoral stem)



ROBODOC® System

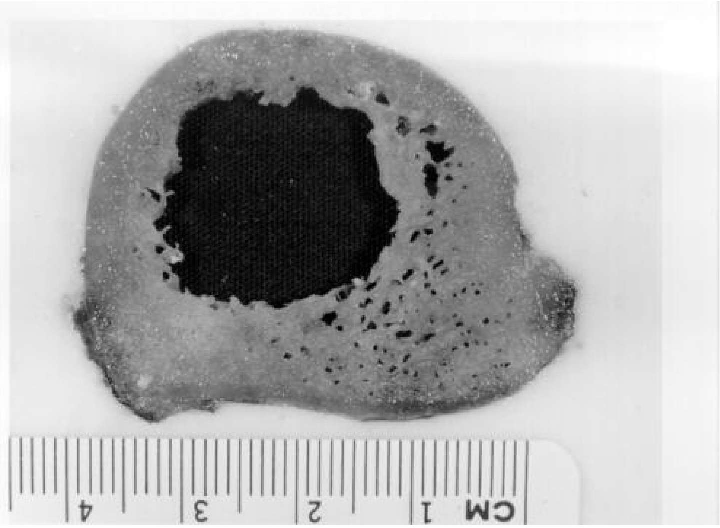
Conventional procedure
(mallet and broach)

Computer-assisted
planning and execution

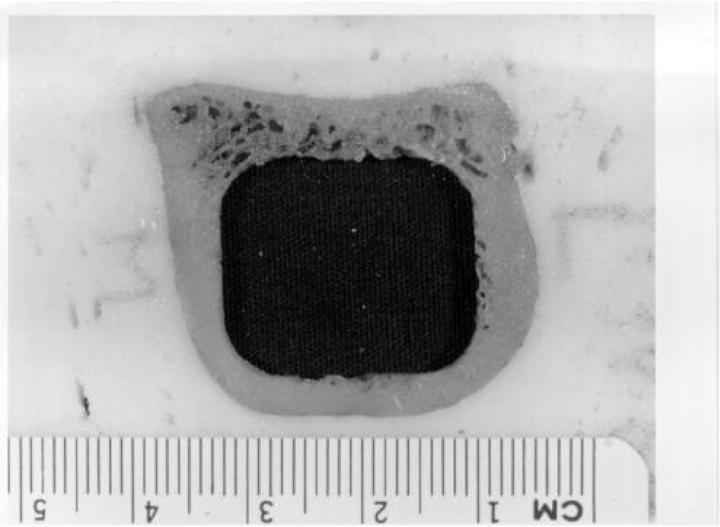


ROBODOC Benefits

- Intended benefits:
  - – Increased dimensional accuracy
  - – Increased placement accuracy
  - – More consistent outcome



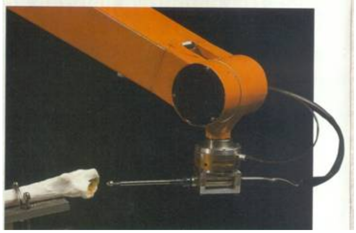
Broach



Robot

ROBODOC History

1986-1988 Feasibility study and proof of concept at U.C. Davis and IBM

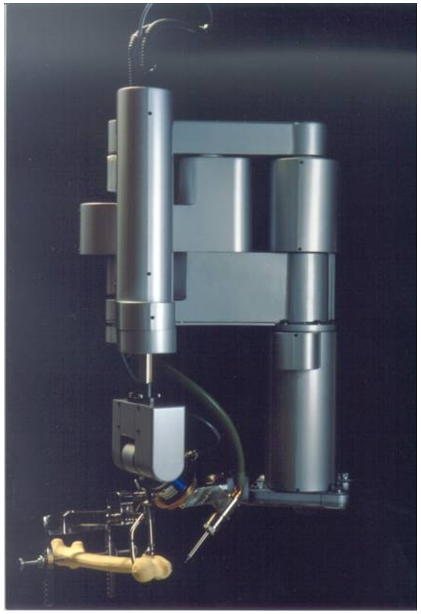


1988-1990 Development of canine system

May 2, 1990 First canine surgery

ROBODOC History

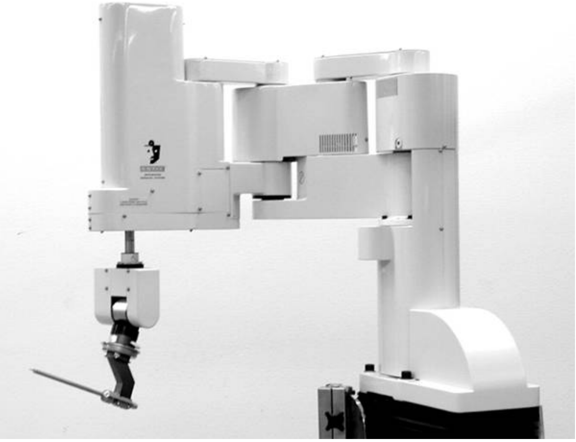
1990-1995	Human clinical prototype
Nov 1, 1990	Formation of ISS
Nov 7, 1992	First human surgery, Sutter General Hospital
Aug 1994	First European surgery, BGU Frankfurt



ROBODOC History

1995-2002 ROBODOC in Europe and Asia

March 1996	CE Mark
April 1996	First 2 installations (Germany)
Nov 1996	ISS initial public offering (NASDAQ)
March 1998	First pinless hip surgery
Feb 2000	First knee replacement surgery



ROBODOC History

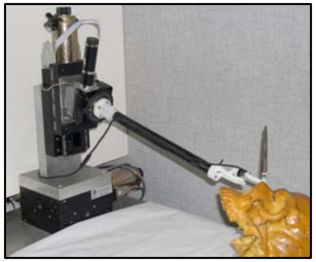
2003-2007	ROBODOC RIP
Oct 2003	Class action lawsuit in Germany
June 2005	ISS “ceases operations”
June 2006	German high court ruling against plaintiff
Sept 2006	ISS resumes operations
June 2007	ISS sells assets to Novatrix Biomedical

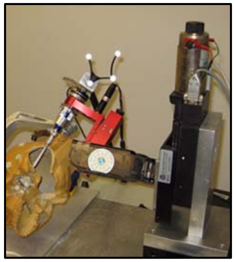
2007-present	ROBODOC reborn
Sept 2007	Curexo Medical formed (Novatrix)
Sept 2007	Curexo files 510(K) with FDA
Feb 2008	Company renamed to ROBODOC, a Curexo Technology Company
Aug 2008	Robodoc receives FDA approval!

ROBODOC Status

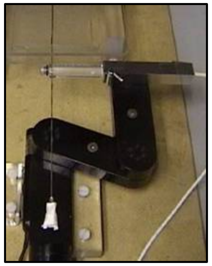
- Approximately 50 systems were installed worldwide
  - Europe (Germany, Austria, Switz., France, Spain)
  - Asia (Japan, Korea, India)
  - U.S. (Clinical trial for FDA approval)
- Over 20,000 hip and knee replacement surgeries
- ROBODOC no longer used in Europe
- One Korean hospital uses system regularly – claim 2,500 surgeries/year
- FDA approval in Aug 2008

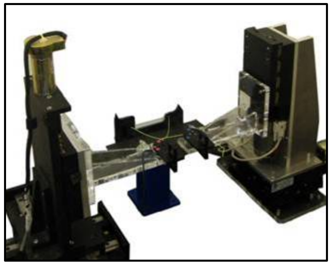
Medical Robotics at JHU

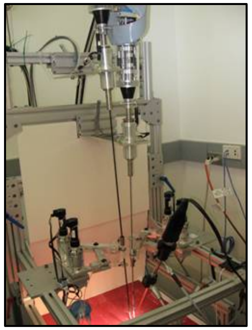

Retinal surgery


Steady hand robot


Research daVinci

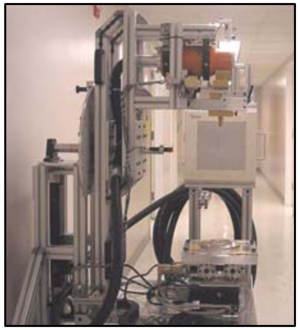

Needle steering


Bimanual manipulation

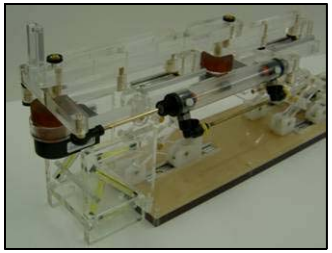

Snake robot

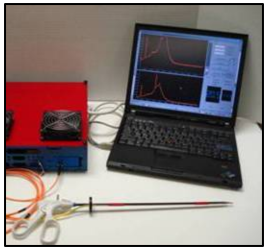

Brachytherapy


Neurosurgery

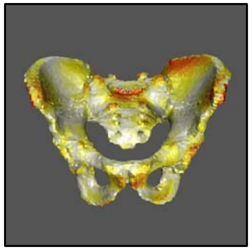

SARRP

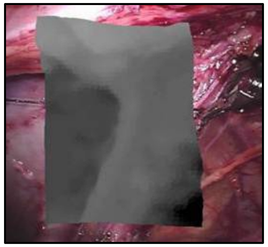

Rodent research


MR-compatible robot


Spectroscopy


Smart retractor


Atlas

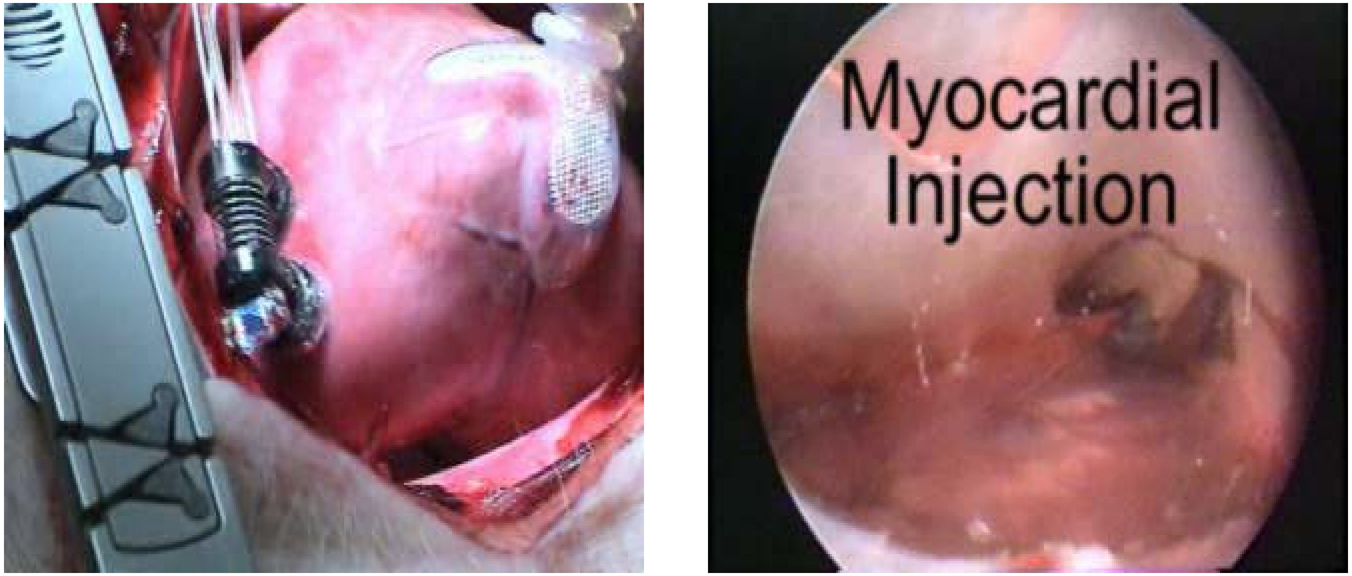

Stereo vision

Control Challenges

- Most medical robots are slow (for safety reasons)
  - Individual joint-level PID control is good enough for position/velocity control
- What about surgery on a beating heart?

HeartLander Robot (CMU)

Miniature mobile robot that adheres to the epicardium and travels to any site for cardiac therapy.



In-vivo testing with beating pig hearts.

Riviere, Patronik, Zenati

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ROBOTICS
INSTITUTE

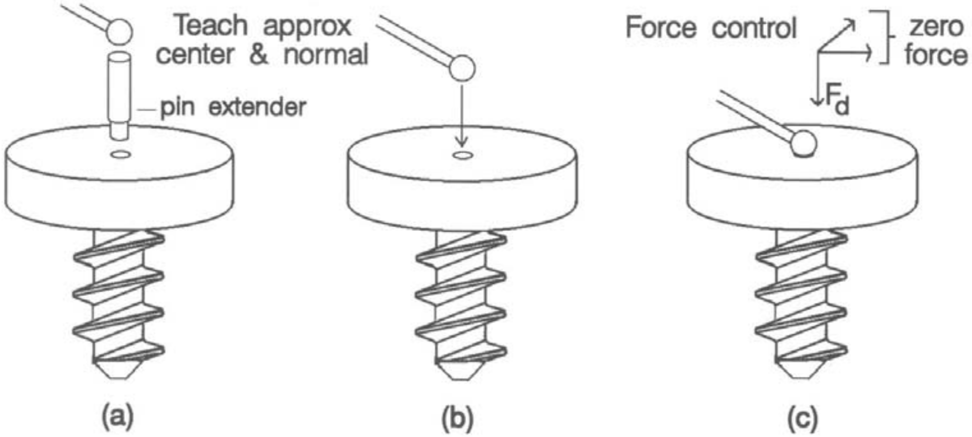
Control Challenges

- Robot must work with surgical team
  - Man/machine partnership vs. automation
- Robot must sense and adapt to its environment
  - Force
  - Tissue properties
  - Vision
  - Intraoperative imaging (CT, MR, Ultrasound)

This talk

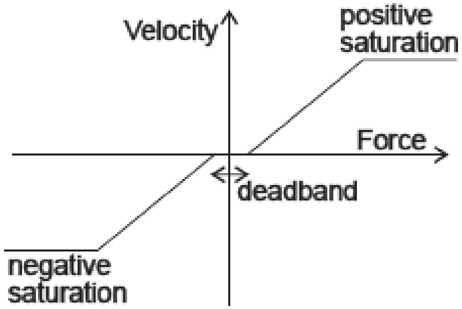
ROBODOC Force Control

- Hand guidance
- Tactile search
- Force-controlled cutting
- Safety threshold

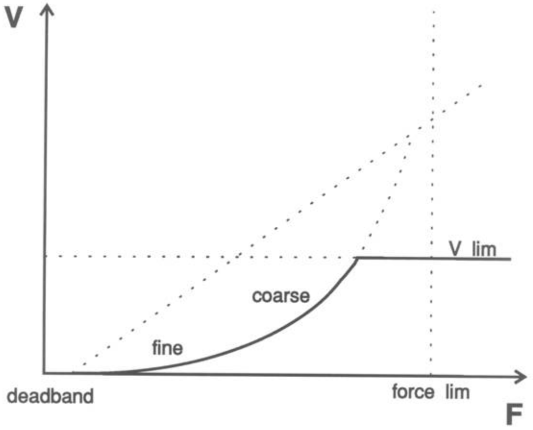


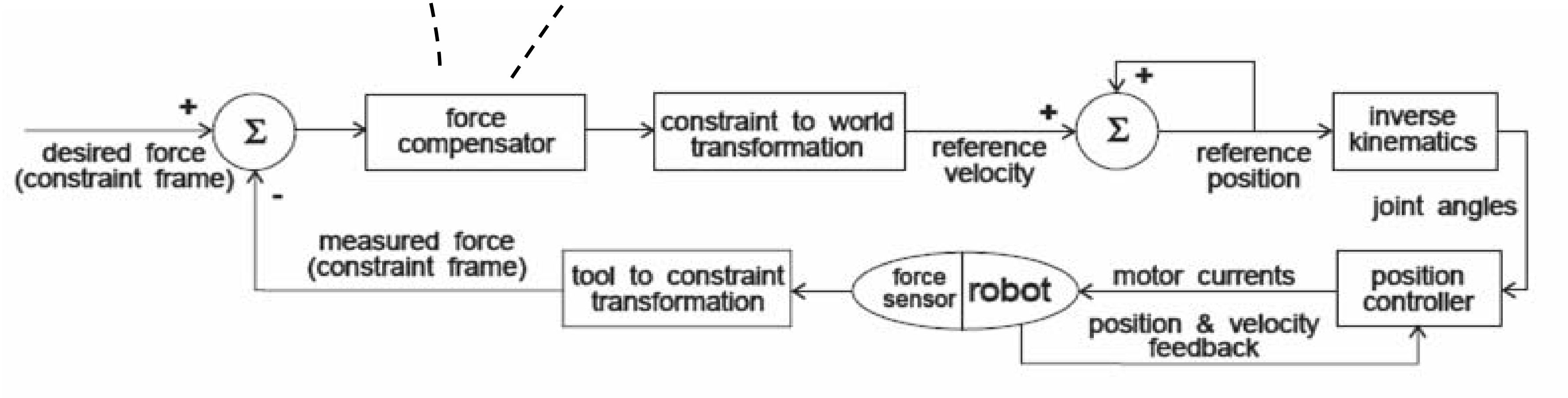
ROBODOC Force Control

Linear Gains



Nonlinear Gains





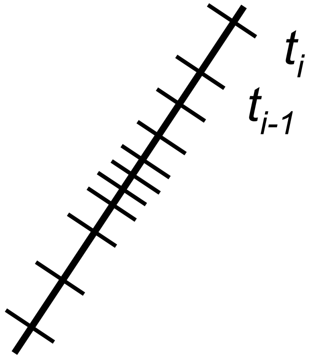
P. Kazanzides, J. Zuhars, B. Mittelstadt, R.H. Taylor, “Force Sensing and Control for a Surgical Robot,” *IEEE Intl. Conf. on Robotics and Auto.*, Nice, France, May 1992

Force-controlled bone cutting

- Problem: ROBODOC uses fixed cutfiles
  - Conservative cut speeds (assume hard bone)
  - Long cutting times
- Solution: Modify cutter feed rate based on measured force
  - Cutfile specifies minimum and maximum feed rates, as well as maximum force
  - System parameters include tool stiffness

Force-controlled bone cutting

- Technical approach: Use “time warping” in trajectory generator
  - All motions are parameterized by time
  - Plan motion at maximum speed, s_{max}
  - Use time t_i from following equation:



$$t_i = t_{i-1} + \Delta t \cdot \arg\max\left(1 - e^{-R(f_{\max} - f(t))}, \frac{s_{\min}}{s_{\max}}\right) \qquad f(t) \le f_{\max}$$

As $f(t) \rightarrow f_{max}$, warp time to reduce speed to s_{min}

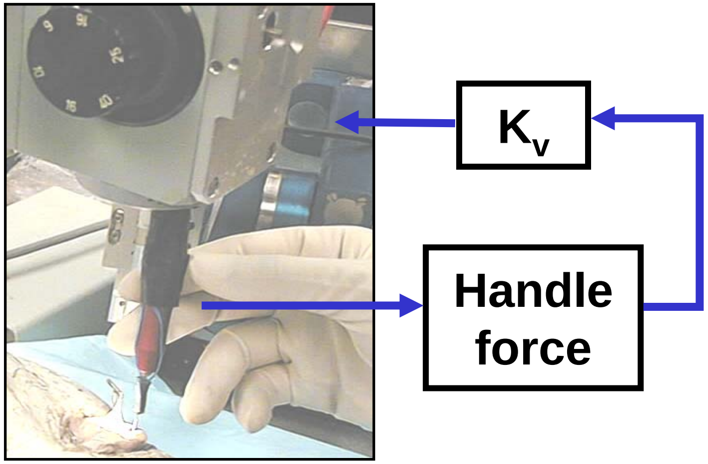
As $f(t) \rightarrow 0$, $t_i \approx t_{i-1} + \Delta T$ (move at s_{max})

If $f(t) > f_{max}$, stop robot and cutter

Cooperative Control and Virtual Fixtures

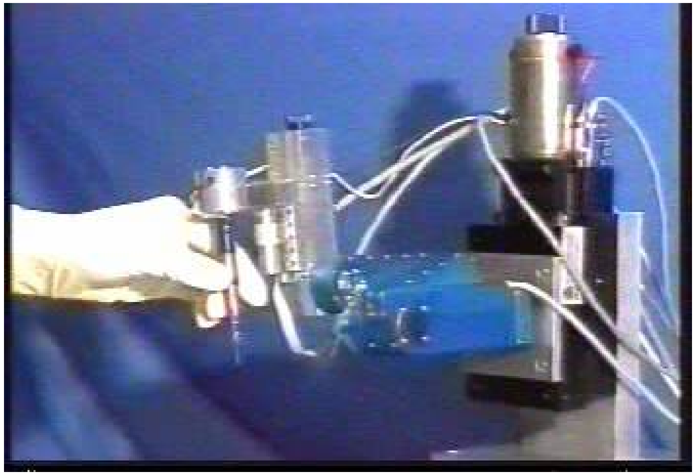
- Generalization of force-controlled guidance and force-controlled cutting
- Steady Hand guidance (JHU)
  - Force-controlled guidance for tremor reduction
- Virtual fixtures
  - Guidance virtual fixtures: constrain motion along a preferred direction
  - Boundary virtual fixtures: prevent motion into a "forbidden zone" (or stay within "safe zone")
  - Hard vs. soft virtual fixtures

Physical Guidance: Steady Hand Guiding for Microsurgery

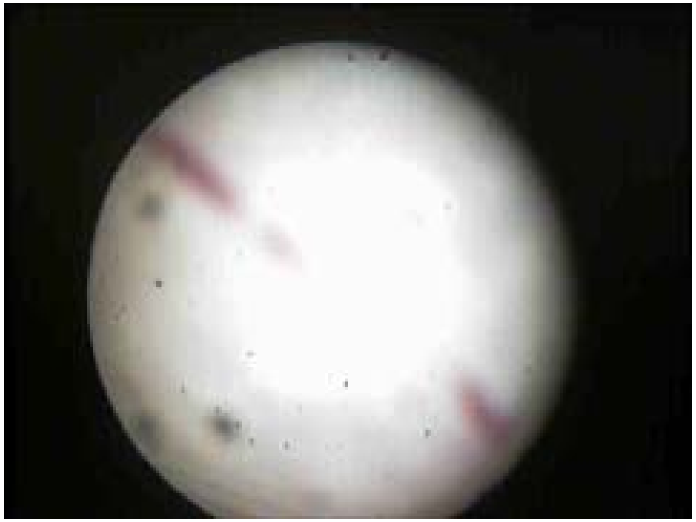


K_v

Handle force



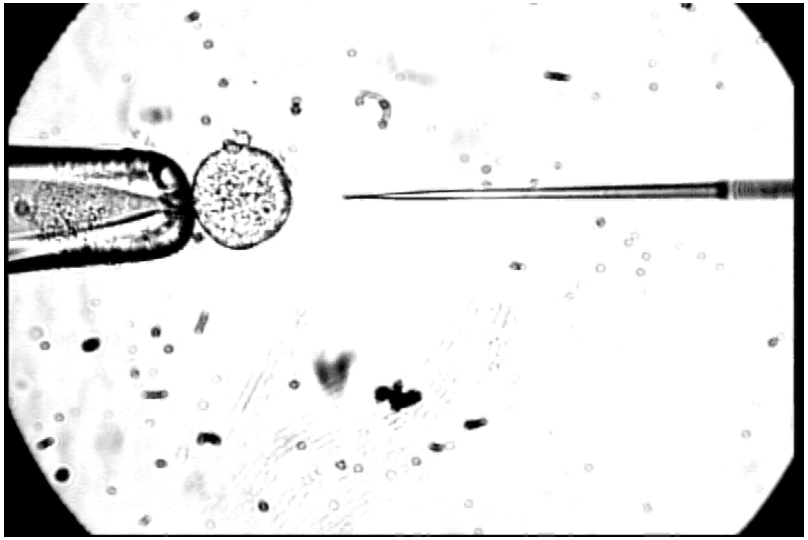
Free hand motion



Steady hand motion

Steady Hand Guiding at the Cellular Level

Kumar, Kapoor, Taylor



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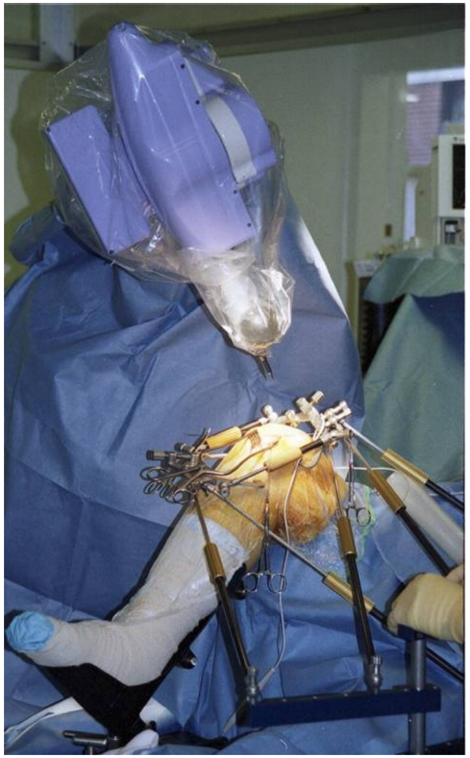
Cooperative Control with Virtual Fixtures: Acrobot Robot (Imperial College, London)

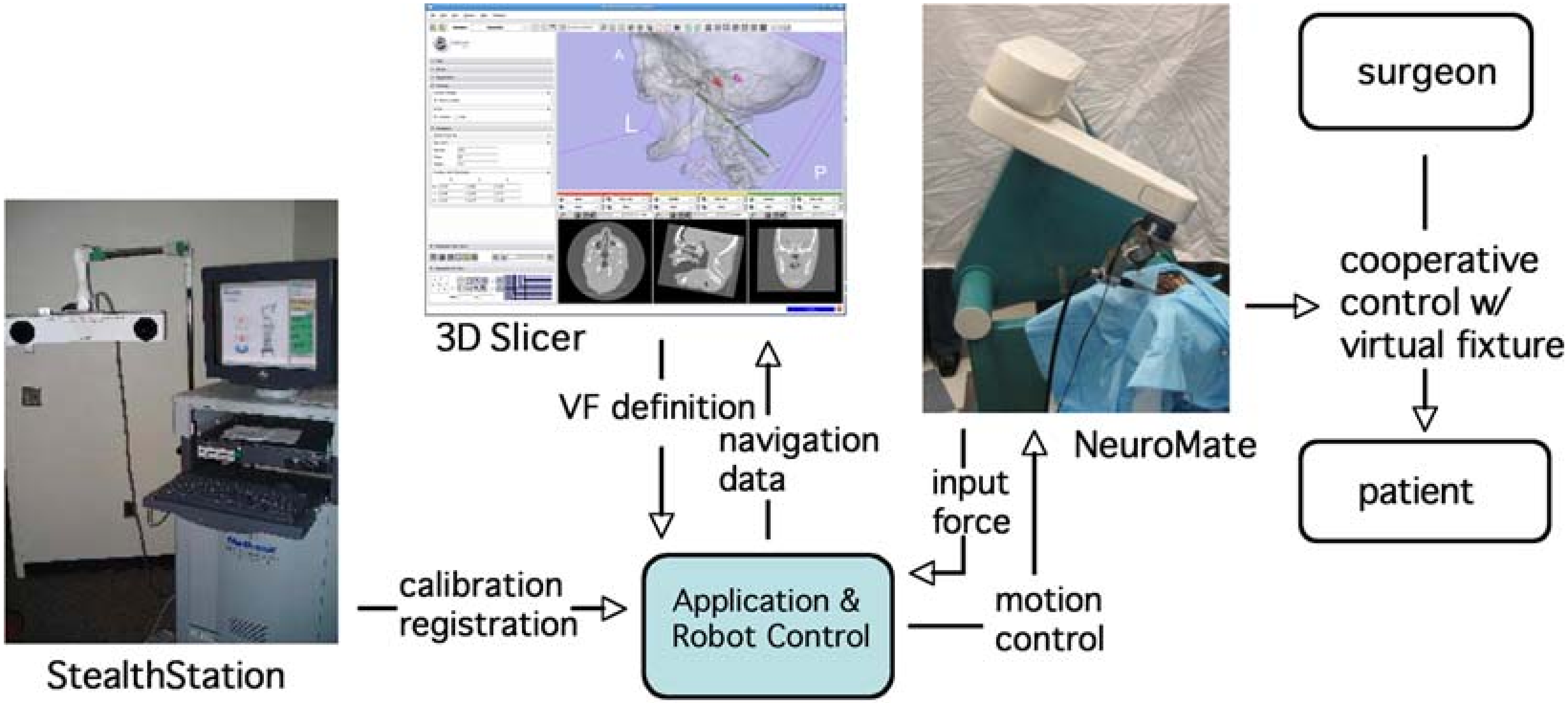
- Uses virtual fixtures (Active Constraint Control) to enable surgeon to execute preoperative plan (machine femur and tibia)



Courtesy of Acrobot Co. Limited, UK

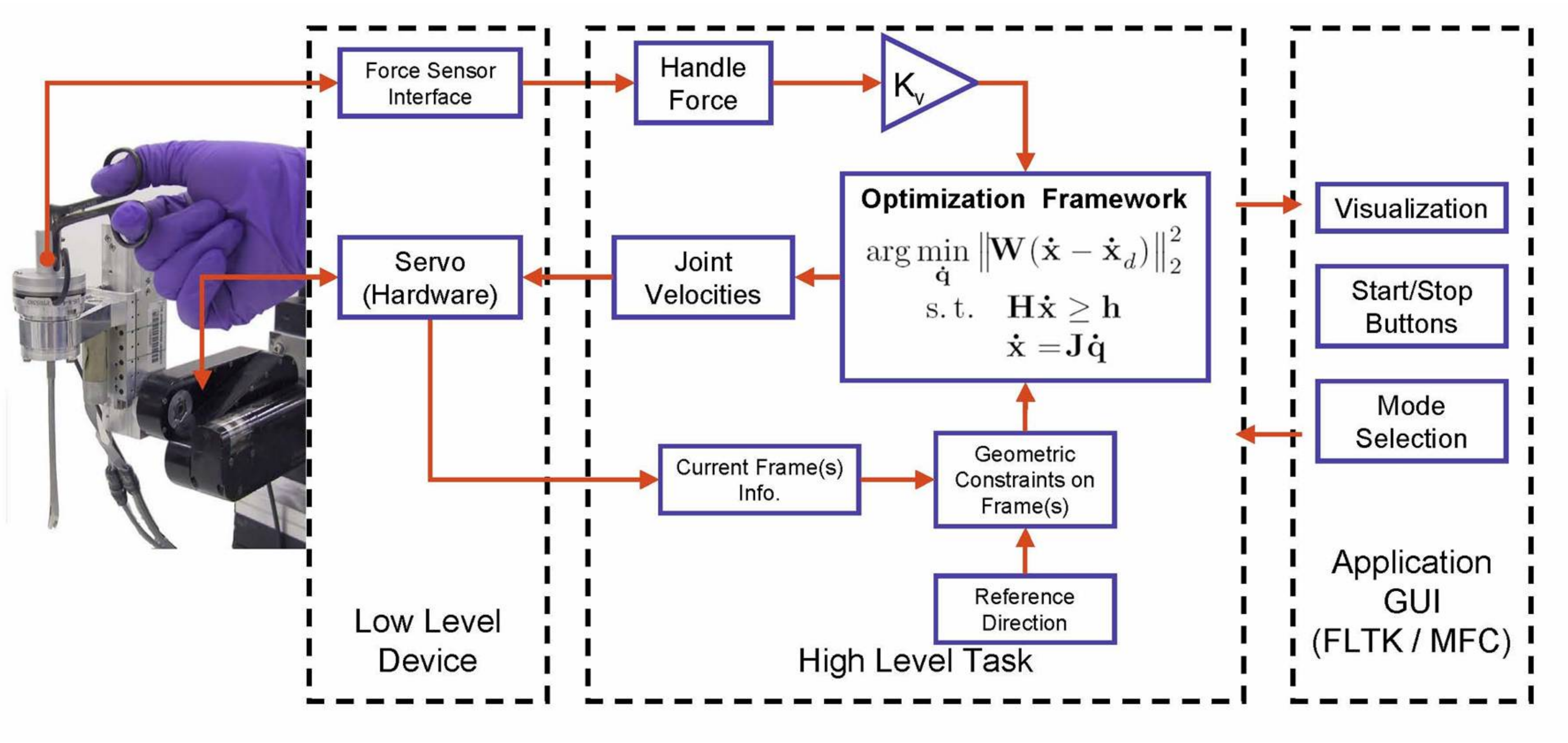
Cooperative Control with Virtual Fixtures: Robot for Skull Base Surgery (JHU)

- Uses virtual fixtures to constrain surgeon to remain inside “safe zone” during skull base drilling



Kazanzides, Xia, Baird, Jallo

Virtual Fixture Implementation: Constrained Optimization



Force Sensor Interface

Handle Force

K_v

Optimization Framework

$$\arg\min_{\dot{\mathbf{q}}} \left\| \mathbf{W}\left(\dot{\mathbf{x}} - \dot{\mathbf{x}}_d\right) \right\|_2^2$$
$$\text{s.t.} \quad \mathbf{H}\dot{\mathbf{x}} \geq \mathbf{h}$$
$$\dot{\mathbf{x}} = \mathbf{J}\dot{\mathbf{q}}$$

Servo (Hardware)

Joint Velocities

Current Frame(s) Info.

Geometric Constraints on Frame(s)

Reference Direction

Visualization

Start/Stop Buttons

Mode Selection

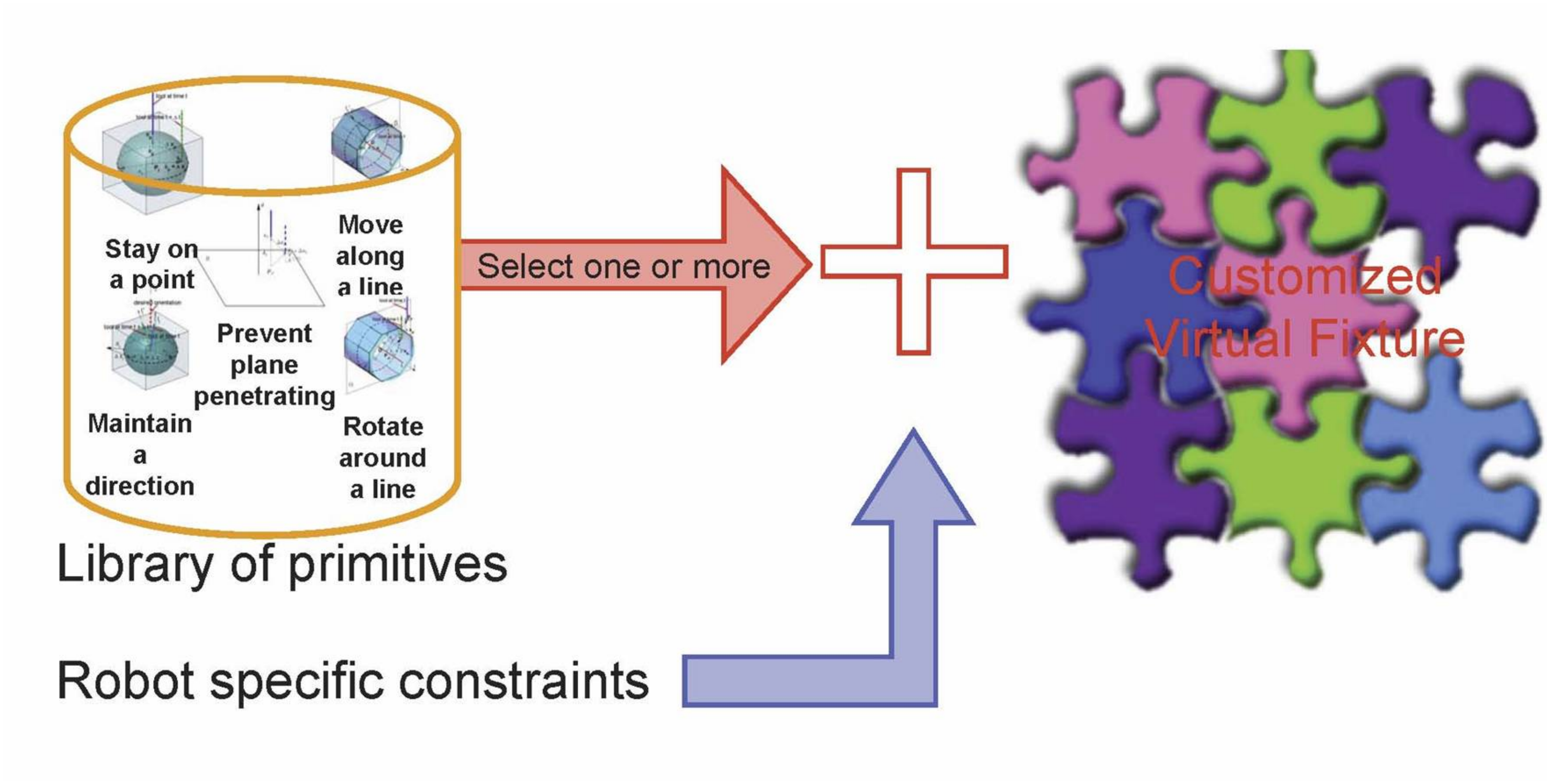
Low Level Device

High Level Task

Application GUI (FLTK / MFC)

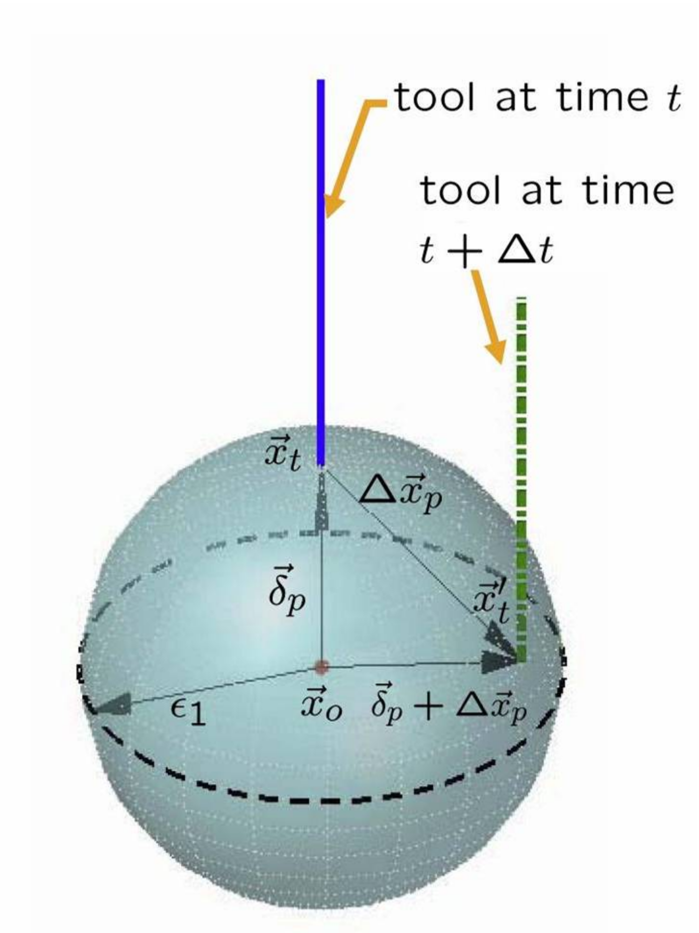
Kapoor & Taylor, 2007

Composition of Virtual Fixtures



Kapoor & Taylor, 2007

Virtual Fixture Primitives:
1) Stay on a point



Constraint: $\|\boldsymbol{\delta}_p + \Delta\mathbf{x}_p\| \leq \epsilon_1$

Polyhedron approximation for sphere of radius ε_1:

$$\begin{bmatrix} c_{\alpha_{1i}}c_{\beta_{1j}} & c_{\alpha_{1i}}s_{\beta_{1j}} & s_{\alpha_{1i}} & 0 & 0 & 0 \end{bmatrix} \cdot (\boldsymbol{\delta} + \Delta\mathbf{x}) \leq \epsilon_1,$$

$$c_{\alpha_{1i}} = \cos\frac{i2\pi}{n}; \quad s_{\alpha_{1i}} = \sin\frac{i2\pi}{n}; \quad c_{\beta_{1j}} = \cos\frac{j2\pi}{m}; \quad s_{\beta_{1j}} = \sin\frac{j2\pi}{m}$$

$$i = 0, \cdots, n-1; \quad j = 0, \cdots, m-1.$$

Yields constraint: $A \cdot \Delta x \leq b$

Conclusions

- Medical robots have distinct differences from industrial robots:
  - Must work with humans (cooperative)
  - Environment (operating room and patient) is relatively unstructured
- Control challenges are primarily at the higher levels:
  - Man/machine interactions
  - Sensor-based control

Conclusions

- Force control widely used:
  - “Steady hand” guidance
  - Virtual fixtures (mechanical guidance)
  - Tactile search
  - Safety
- High-performance computers enable “real-time” numerical optimization

Acknowledgements

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  - Russell Taylor
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TATRC Cutting Edge Medical Technology