



**NSF Engineering Research Center for
Computer-Integrated Surgical Systems and
Technology**



Surgical Assistance

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Professor of Computer Science**

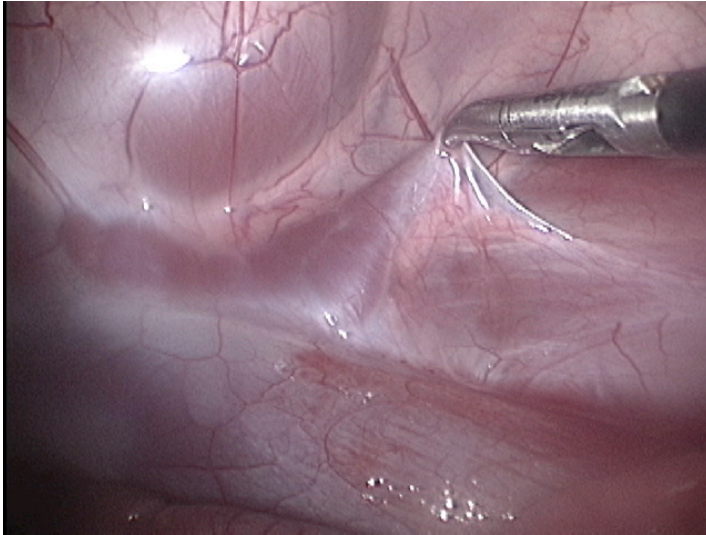
<http://www.cs.jhu.edu/~hager/Public/MICCAI-Tutorial.pdf>



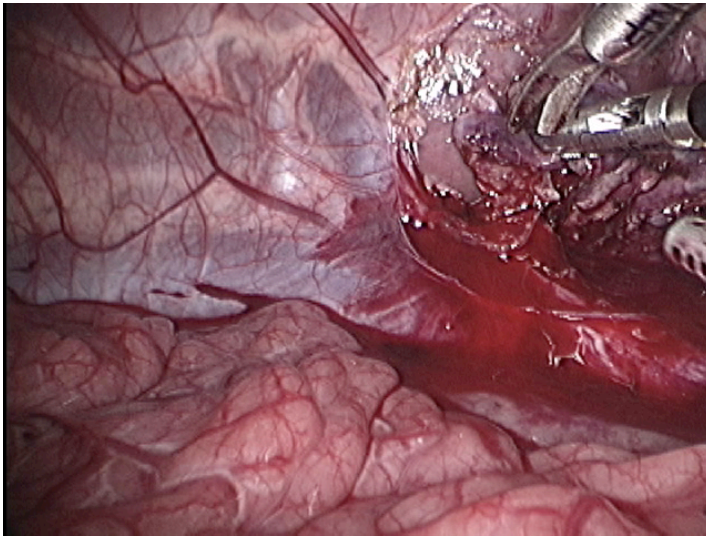
Some Motivating Examples



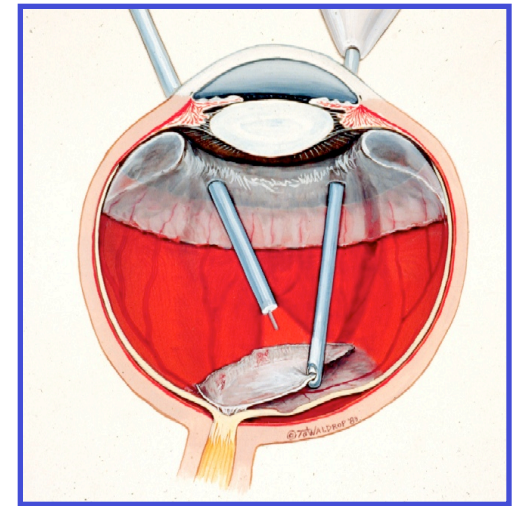
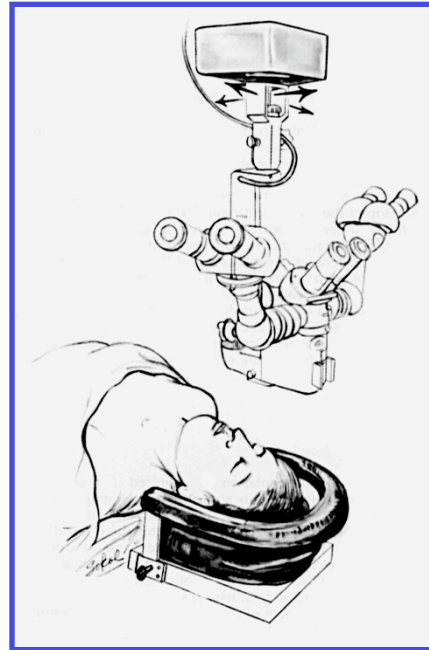
An Example: Laparoscopic Surgery



**Issues: Remote dexterity +
adequate visualization**



An Example: Vitreoretinal Surgery



Key issue: precision of motion

From "Ophthalmic Surgery" by The Wilmer Ophthalmological Institute

Engineering Research Center for Computer Integrated Surgical Systems and Technology

An Example: MIS of the Upper Airway

Haptic information deficiency

View limited by soft tissue

Multiple tools

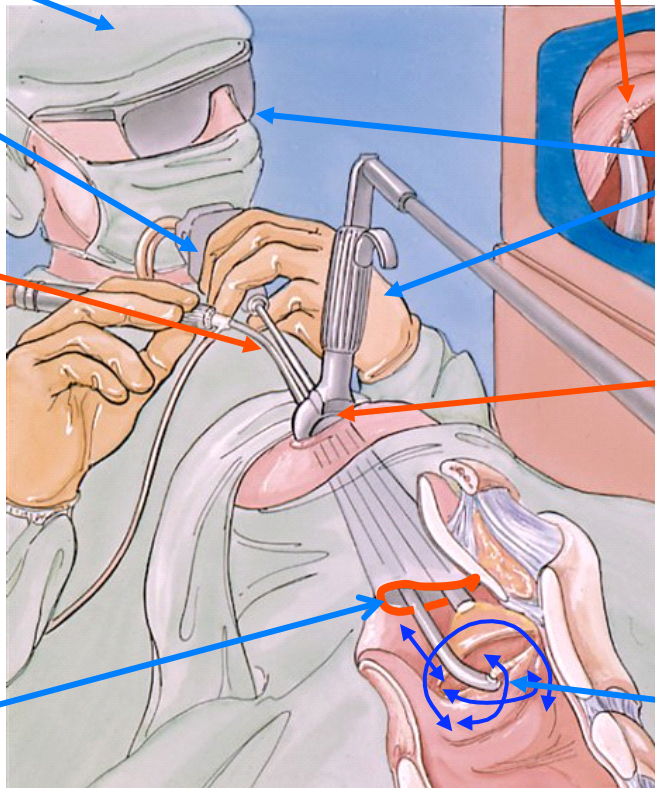
Long rigid instruments:
**provide no
reconstructive
capability**

Hand-eye
coordination

Predetermined
entry port

4 DoF motion
constraint

**No distal
dexterity**



Key issues: remote dexterity and good visualization

N. Simaan, R. Taylor, P. Flint

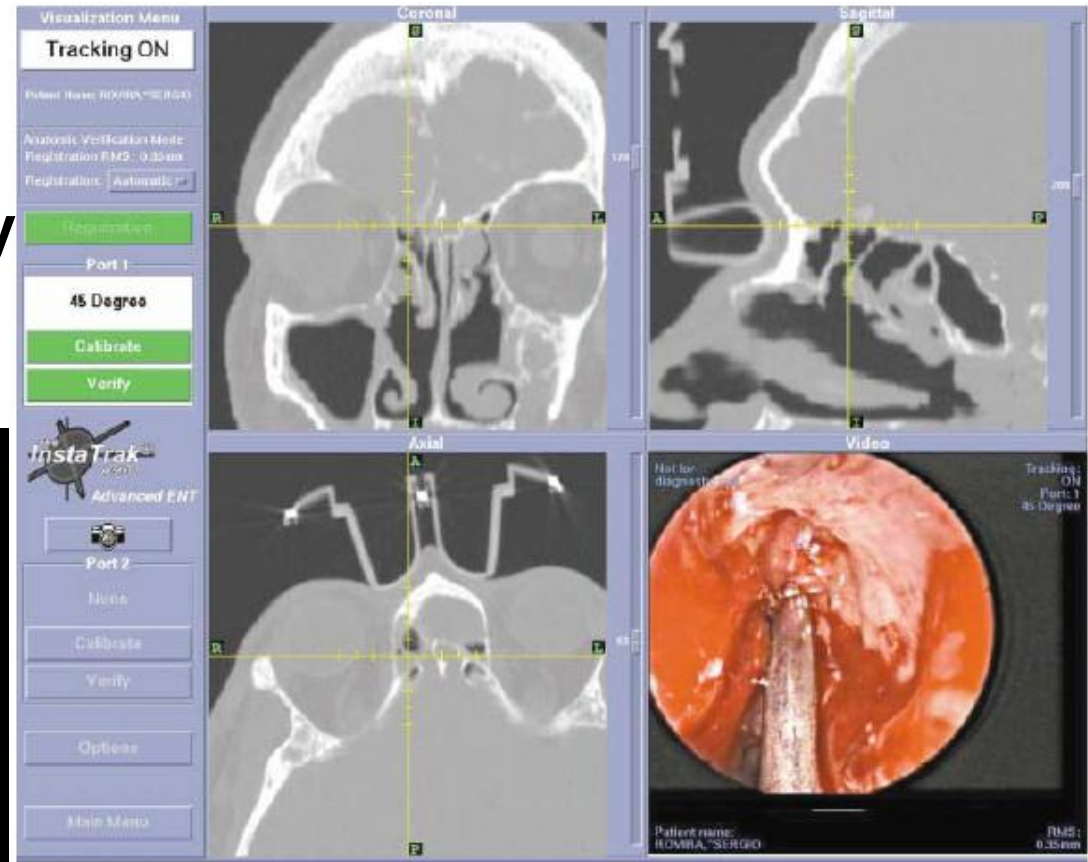
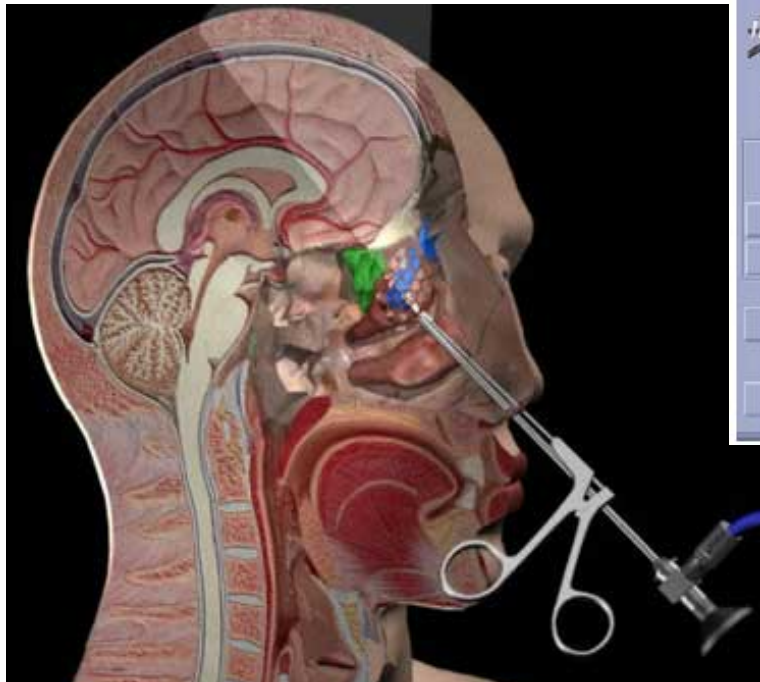
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Engineering Research Center for Computer Integrated Surgical Systems and Technology



An Example: Endoscopic Sinus Surgery

Key Issues:
Visualization
Remote dexterity
Precision



D. W. Kennedy, W. E. Bolger , and S. J. Zinreich

Diseases of the Sinuses: Diagnosis and Management. 2001.

An Example High Precision Ultrasound Guided Needle Placement

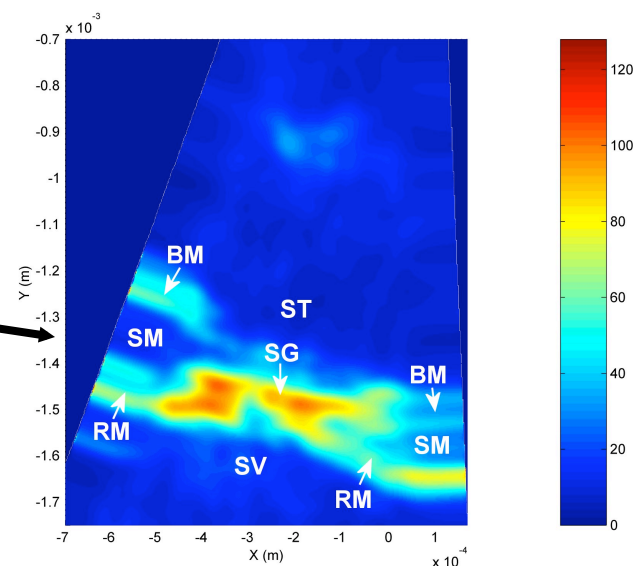
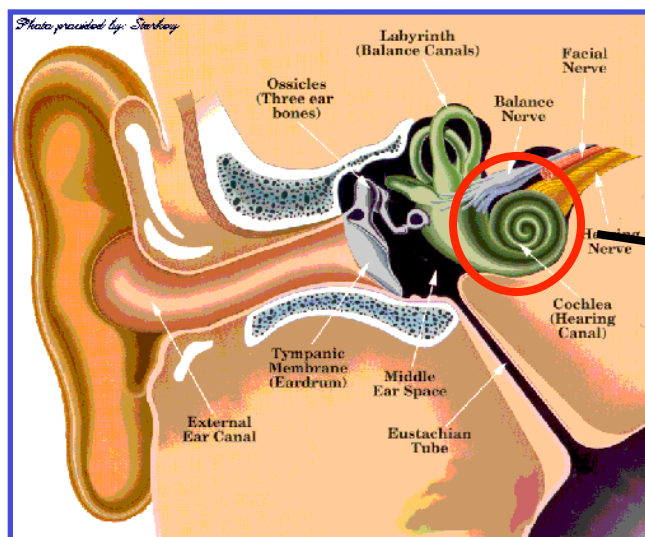
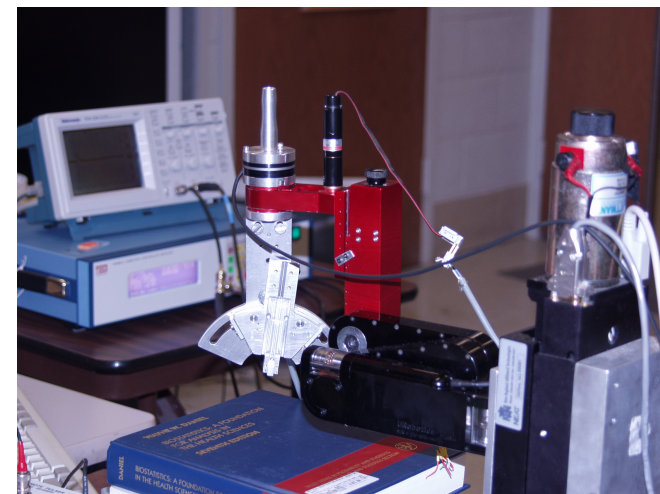
Rothbaum/Roy/Mustafa/Niparko/Francis/Whitcomb

Key issues:

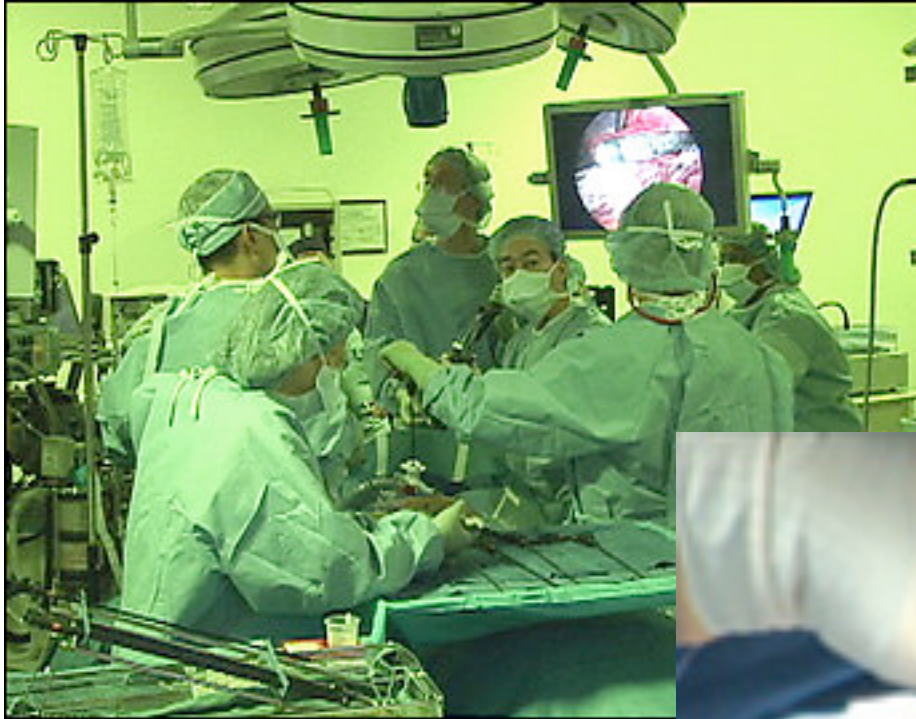
Precision of motion

Sensing

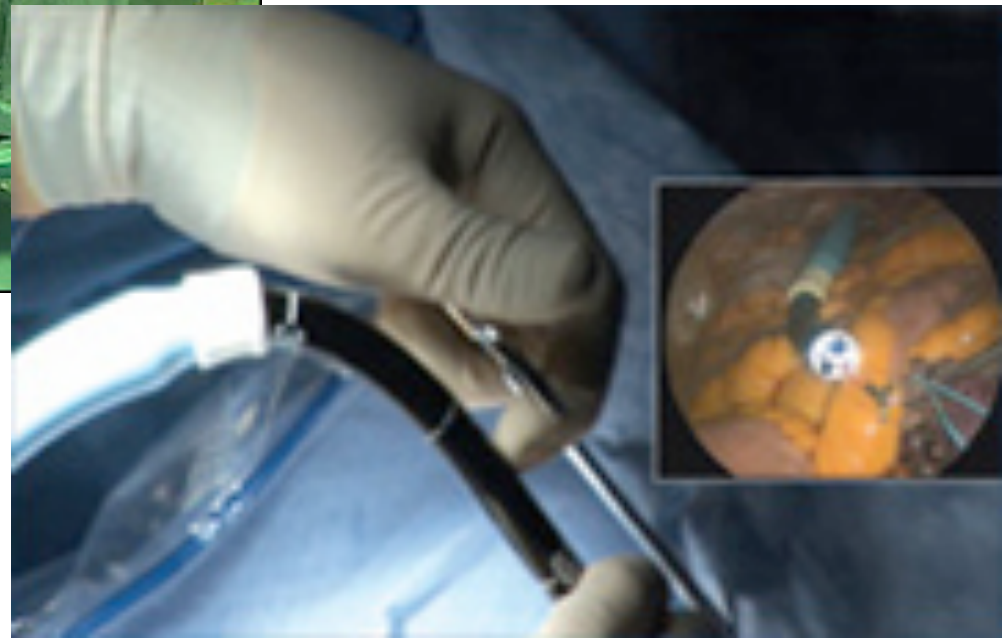
Visualization



An Example: NOTES

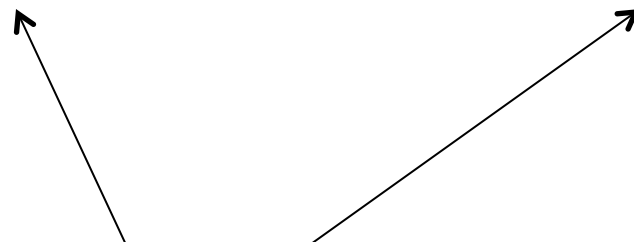


Key issues:
miniaturization
remote dexterity,
visualization,
navigation



What Are (Some of) the Issues?

	Dexterity	Precision	New Sensing	Information Visualization
MIS	+++	-	+	+
Retina	+	+++	++	+
Sinus	++	+++	+	+++
Throat	+++	+	-	-
Ear	-	+++	+++	++
NOTES	+++	+	??	++


This Tutorial

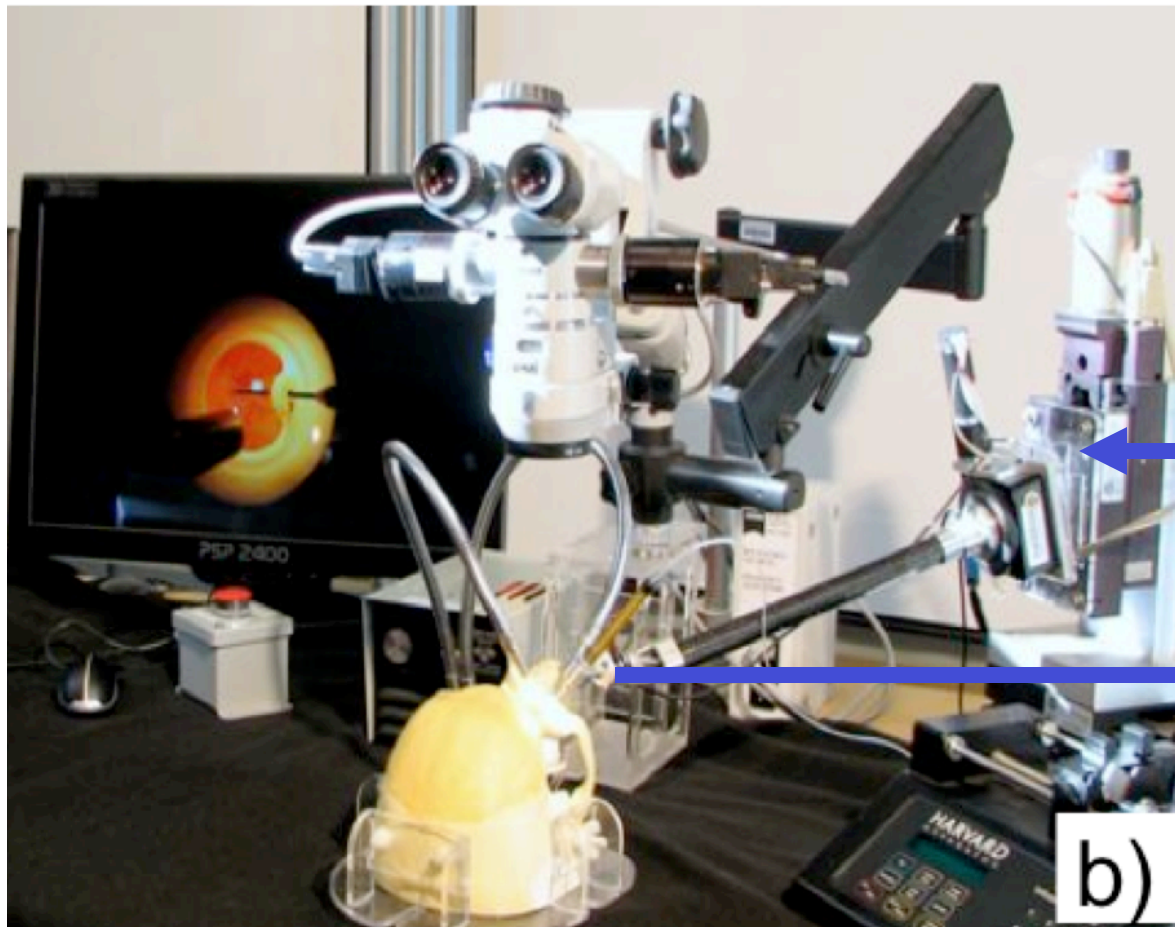


Some Assistant Robot Paradigms



JHU Steady-Hand Robot

- Admittance control
- Remote center of motion
- Micron-scale accuracy



Velocity (v)

K_v

Handle
force (f)

$$v = K_v f$$

The diagram illustrates a master-slave teleoperation system for a surgical microscope. It consists of the following components and flow:

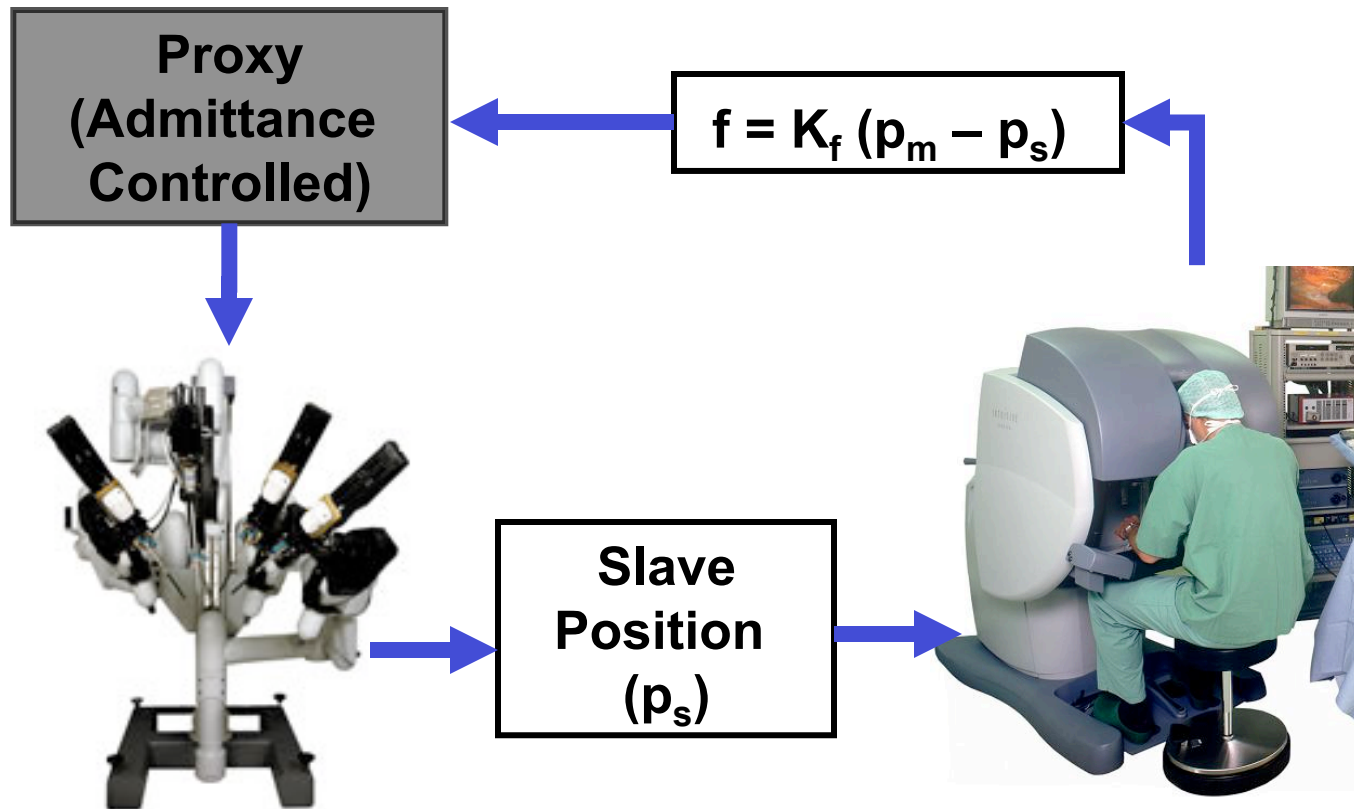
- Master Position (p_m)**: A box representing the master's position, which receives input from the surgeon and sends a signal to the force feedback block.
- Force (f)**: A box representing the force feedback signal, which receives input from the stiffness block and sends a signal to the master position box.
- Stiffness (K_f)**: A box representing the stiffness gain, which receives input from the master position box and sends a signal to the force feedback box.
- Slave Position (p_s)**: A box representing the slave's position, which receives input from the microscope and sends a signal to the force feedback block.
- Force Feedback Equation**: A box at the bottom containing the equation $f = K_f (p_m - p_s)$, which defines the relationship between the force feedback signal and the positions of the master and slave.

The diagram also includes two photographs: a surgical microscope on the left and a surgeon operating the master device on the right.

- Copyright © GD Hager, 2009



Intuitive Surgical da Vinci System



J. J. Abbott, G. D. Hager and A. M. Okamura, "Steady-Hand Teleoperation with Virtual Fixtures," 12th IEEE International Workshop on Robot and Human Interactive Communication (RO-MAN 2003), pp. 145-151.

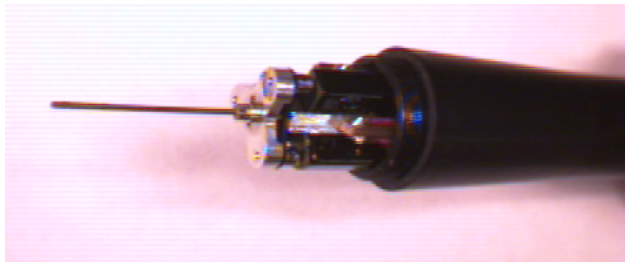
J. J. Abbott and A. M. Okamura, "Pseudo-admittance Bilateral Telemanipulation with Guidance Virtual Fixtures," Int. J. Robotics Research, 26(8):865-884, 2007.

Ungrounded Devices

Riviere et al. (CMU)

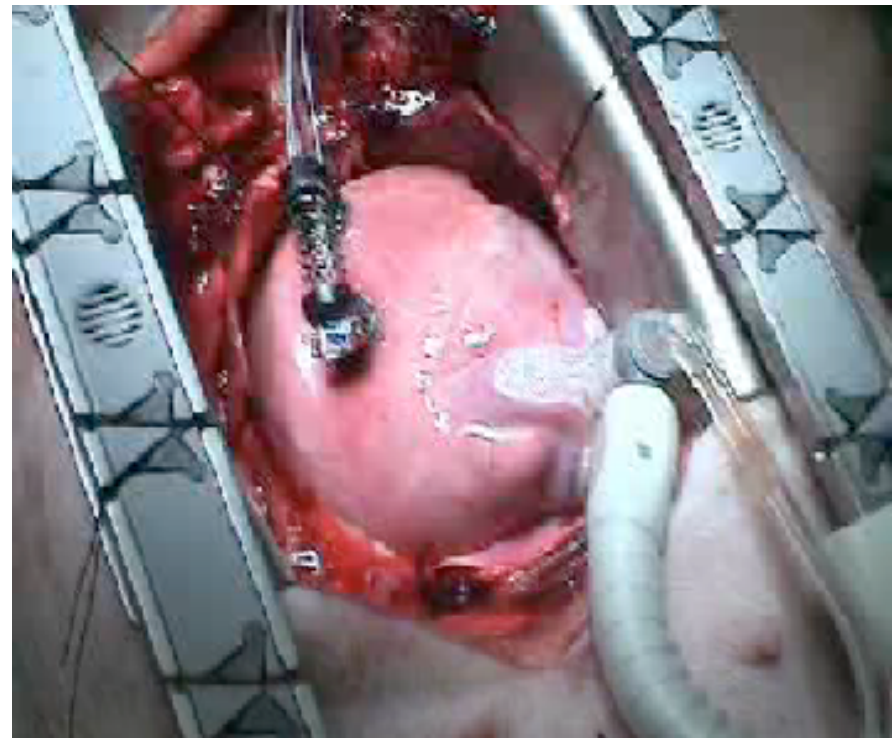
Micron incorporates motion sensing and endpoint control

- Small, hand-held design
- Active tremor cancellation
- Active tip control



Precise control of piezoelectric actuators is needed for effective active tremor compensation.

- Heartlander: mobility inside the body



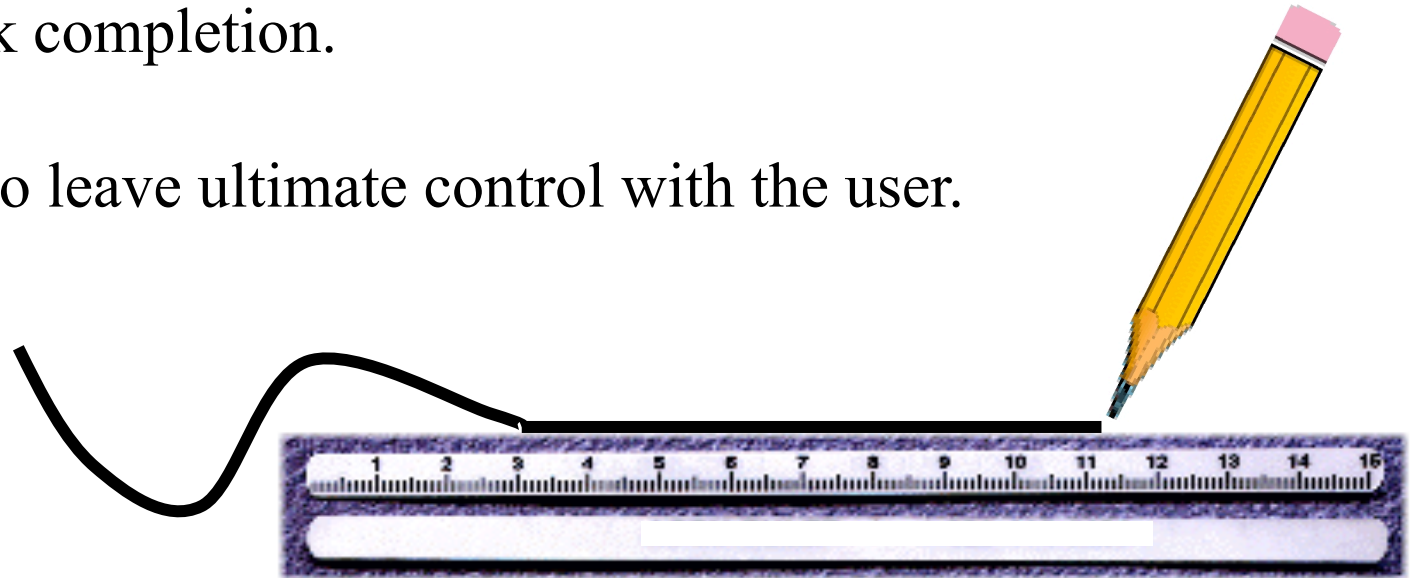
Enhancing Precision



Virtual Fixtures

Perceptual overlays designed to enhance performance.

- Bridge the gap between autonomous robots and direct human control.
- Assist the human operator in safer, faster, and more accurate task completion.
- Designed to leave ultimate control with the user.



Virtual fixtures have appeared under various aliases ...

- Virtual fixtures —

Rosenberg 1993, Park *et al.* 2001, Payandeh and Stanisic 2002, Abbott and Okamura 2003, Kuang *et al.* 2004, Park *et al.* 2004, Li and Taylor 2004, Aarno *et al.* 2005

- Virtual paths and virtual surfaces — Gillespie *et al.* 2001, Moore *et al.* 2003

- Virtual mechanisms — Joly and Andriot 1995, Micaelli *et al.* 1998

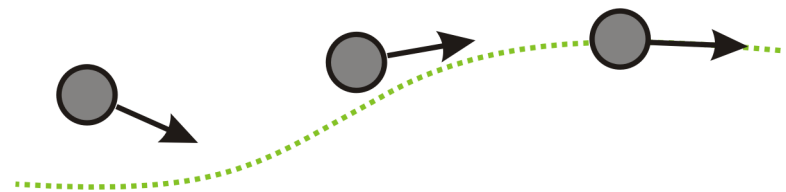
- Synthetic fixtures — Sayers 1999

- Haptically augmented teleoperation — Turro and Khatib 2000



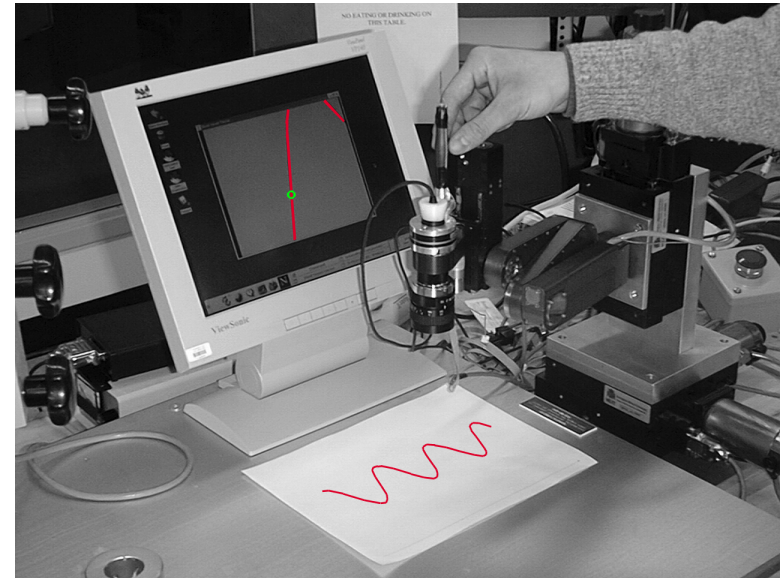
Virtual fixtures fall into two categories

- **Forbidden-region virtual fixtures** prevent the slave from entering forbidden regions of the workspace.
- **Guidance virtual fixtures** keep the slave moving along desired paths or surfaces through the workspace.



Control for Virtual Fixtures

Problem: *Design an admittance control that provides anisotropic compliance based on a given path.*



- Hard constraint
 - The tool is completely constrained to move on a reference path
- Soft constraint
 - The tool is not entirely constrained. The reference direction is considered a *privileged direction* in space

Some Basics

- *Preferred directions* D constitute n local velocity directions of “desirable” motion
- Define the *span* of D as $[D] = D'(D'D)^+D$ where $+$ is a Moore-Penrose pseudo-inverse
- Define the *kernel* of D as $\langle D \rangle = (I - [D])$
- Note these are orthogonal scale-preserving projection operators



Immediate Observation

Given directions $D = D(t)$, force inputs $f = f(t)$
and a system with velocity control $v = v(t)$, do

$$v = c ([D] + c_{\tau} \langle D \rangle) f$$

where c is the overall compliance and $c_{\tau} \in [0,1]$ is an
attenuation factor

$c_{\tau} = 0$ is a *hard virtual fixture*

$c_{\tau} > 0$ are *soft virtual fixtures*



Closed-Loop Virtual Fixtures: Basic Idea

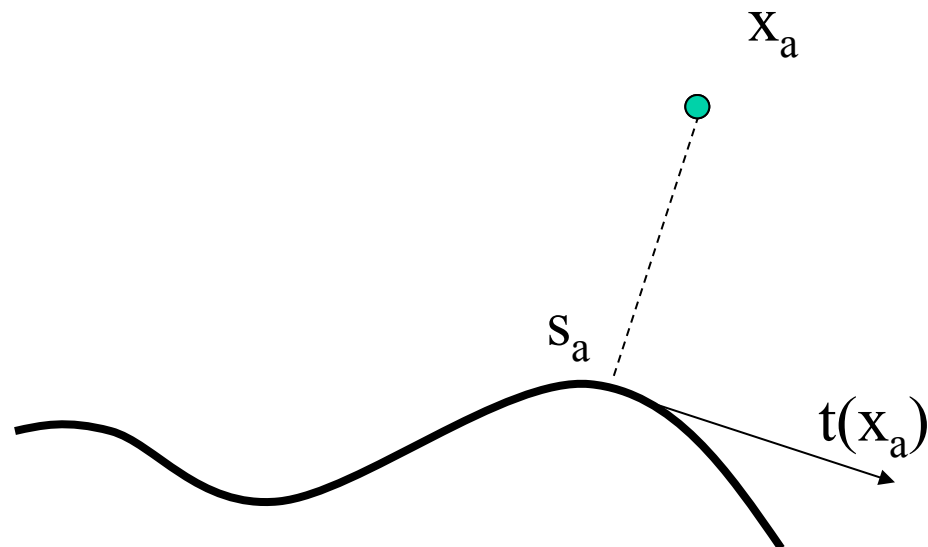
Consider

- curve $p(s)$
- tool tip x_a
- closest point $p(s_a)$ to x_a

The preferred direction δ_p is the normalized tangent

$$t(x_a) = \frac{d}{ds} p(s) \big|_{s=s_a}$$

$$\delta_p(x_a) = \frac{t(x_a)}{\|t(x_a)\|}$$



Closed Loop Virtual Fixtures: Basic Idea

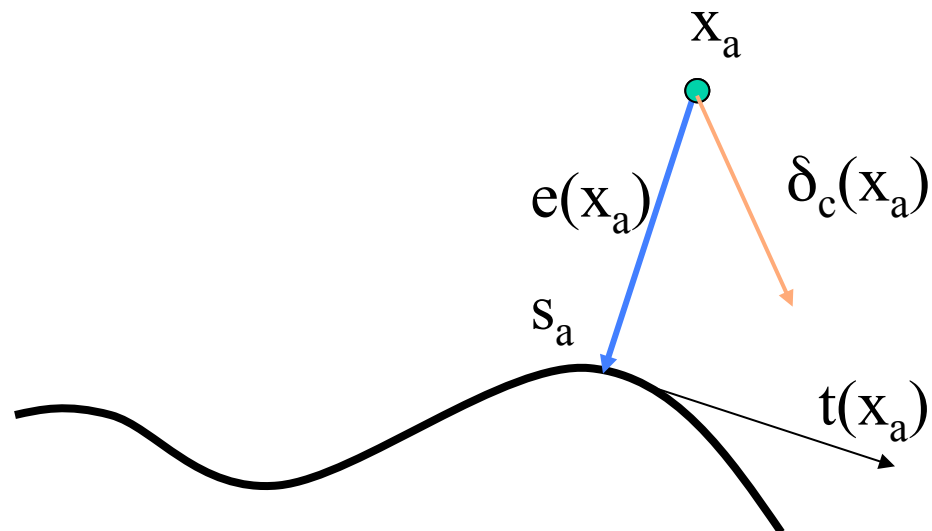
Now, define an error that returns tool to p

$$e(x_a) = p(s_a) - x_a$$

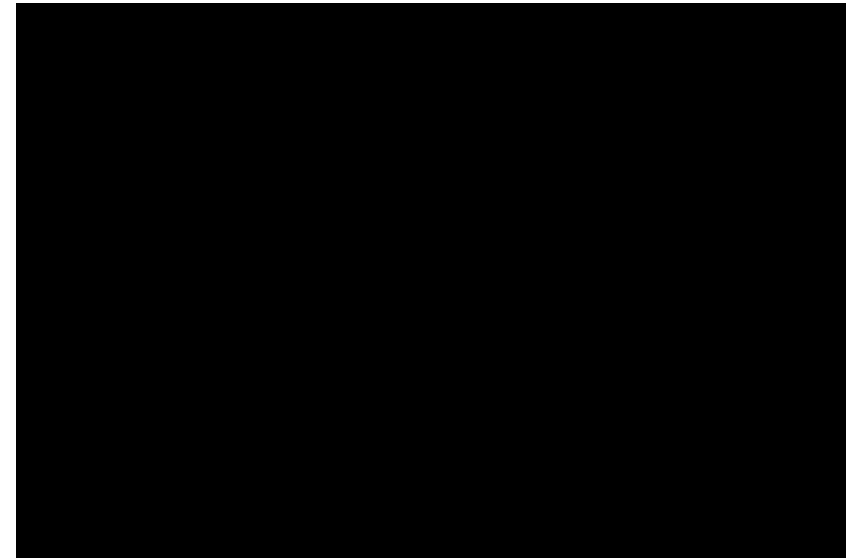
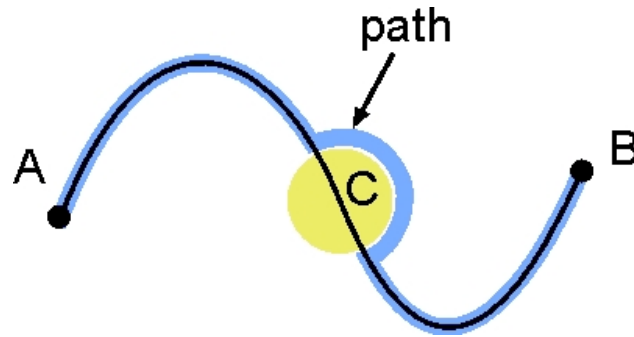
Define a new reference direction with this error term

$$\delta_c(x_a) = \delta_p(x_a) + k_d e(x_a)$$

where $k_d > 0$ is a scalar gain

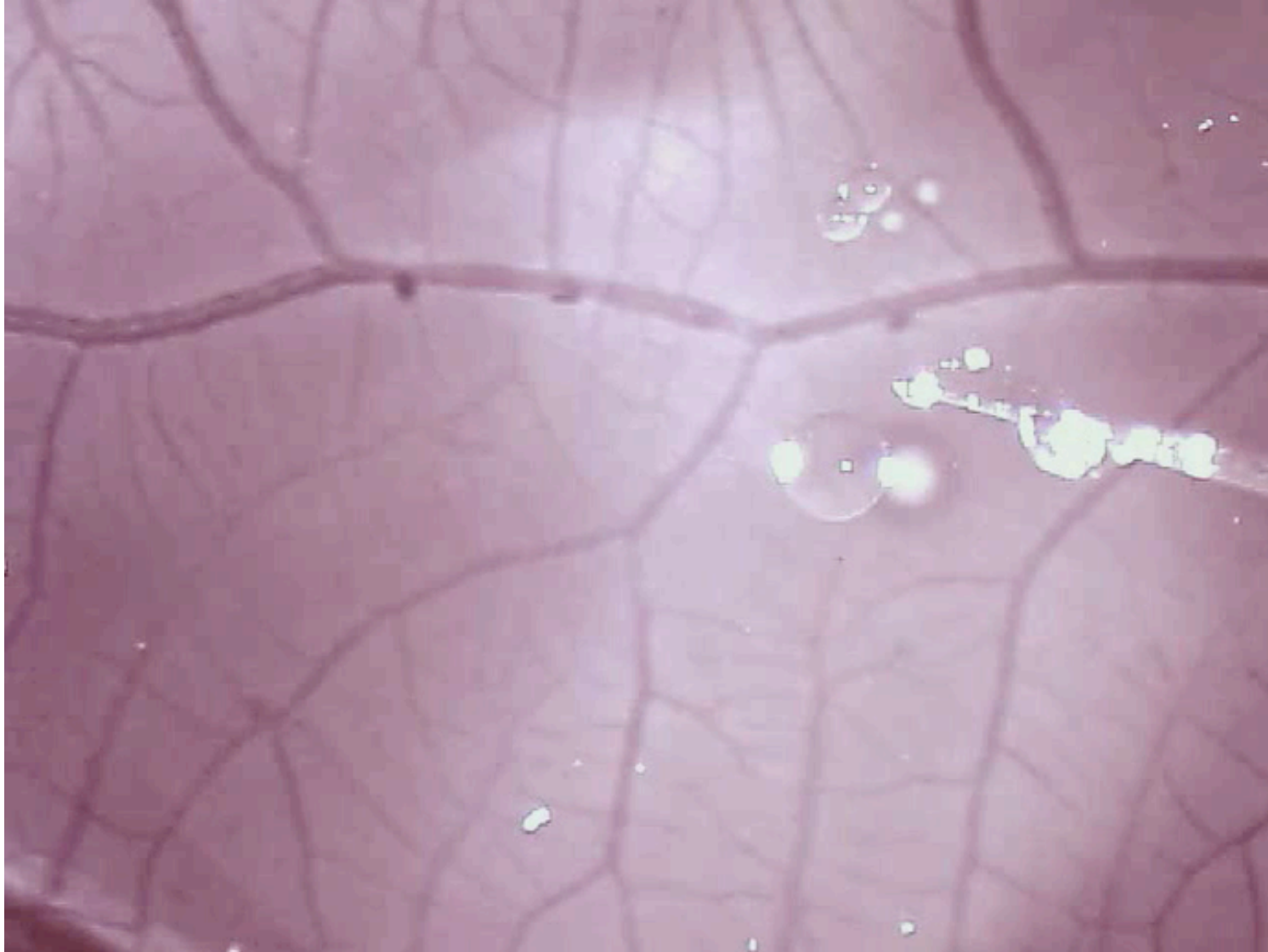


Effect of Varying Compliance



c_{τ}	Average error (pixels)	Execution time (sec)	Obst. avoidance time (sec)
0	0.59	16.38	N/A
0.3	0.84	21.16	8.71
0.6	2.08	17.49	4.36
1 (fast)	7.06	19.55	4.58
1 (precise)	2.25	39.29	7.85

Admittance Guidance for Cannulation



Adding Speed Control

Many surgical gestures have a dynamic component ---
thus the need for **speed control**

Given a trajectory $T(s)$ with associated speed $v(s)$, compute at every time t the speed error:

$$v_e = v^*(s) - ||v(t)||$$

Turn error into a gain:

$$K_s(v_e) = \lambda_s e^{k_p v_e}$$

And modify the virtual fixture control law:

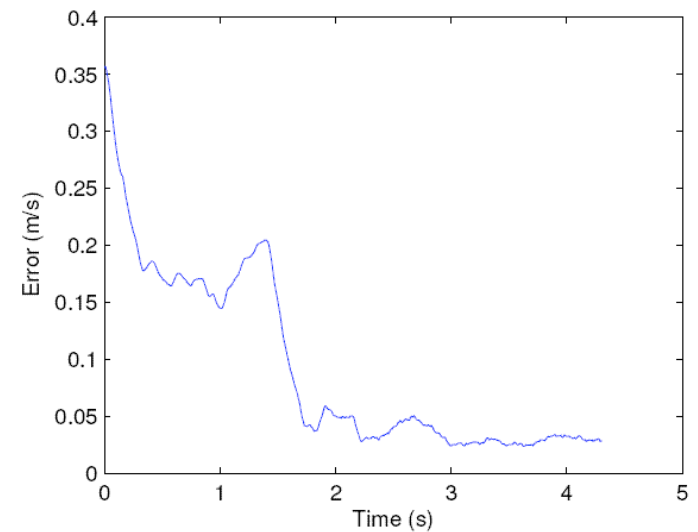
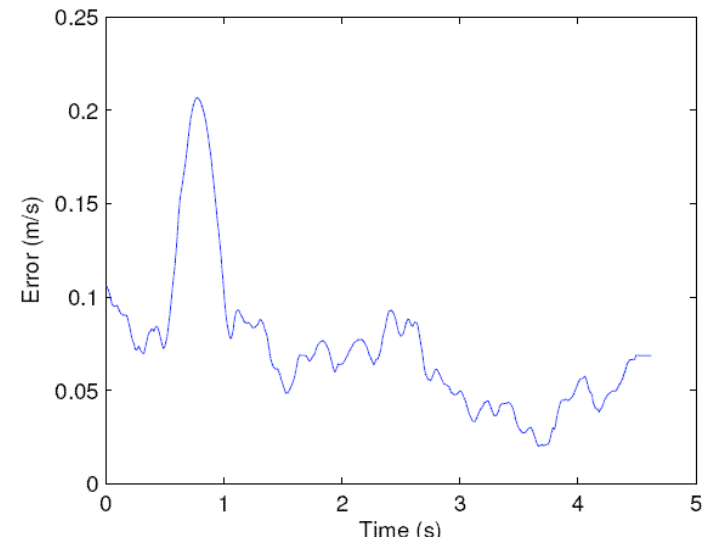
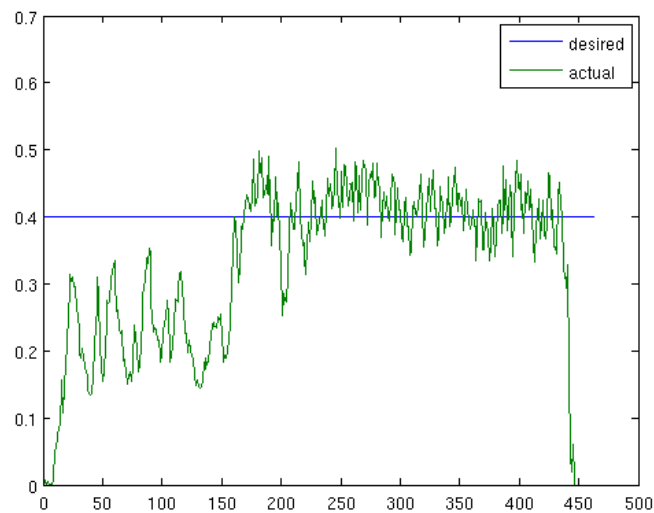
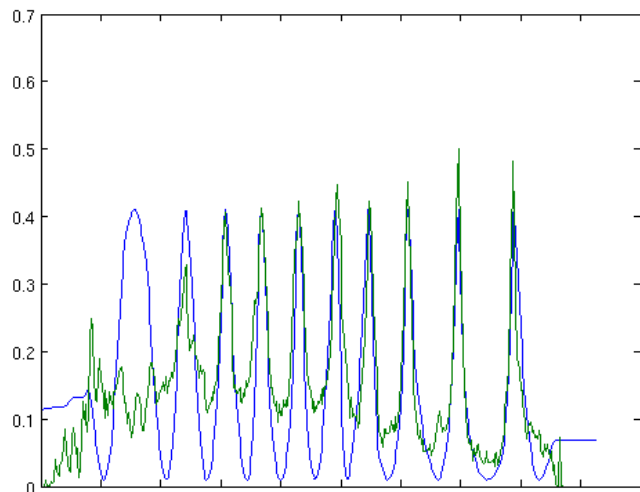
$$v(t) = K_s(v_e) ([D] + c_\tau <D>) f$$

Intuition: if $v^*(s) = ||v(t)||$, a unity gain
if v_e is positive, a large gain
if v_e is negative, a small gain



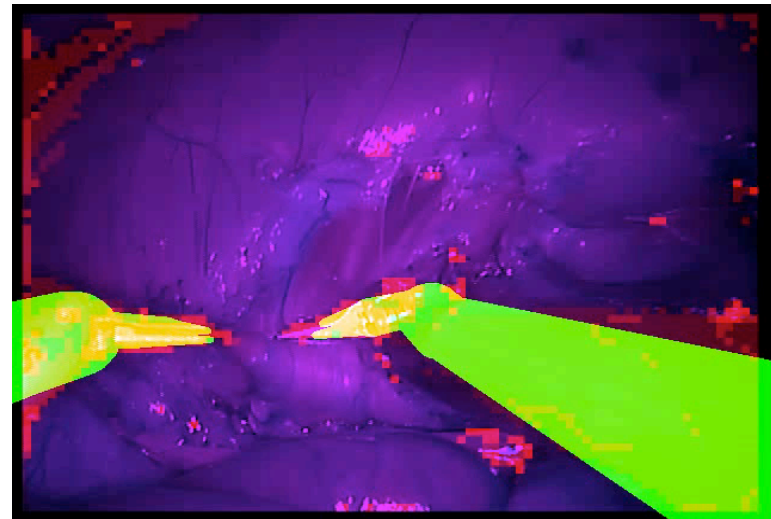
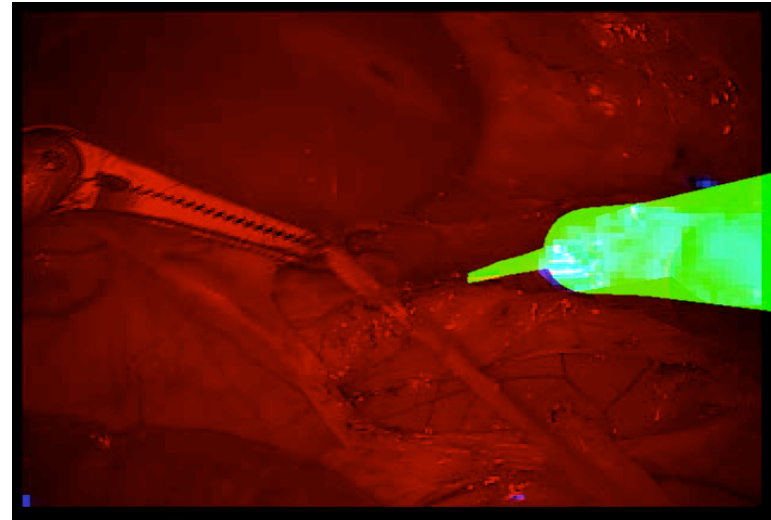
Haptics-Only Speed Matching Test

Z. Pezzementi, G. D. Hager, A. M. Okamura, Dynamic Guidance with Pseudoadmittance Virtual Fixtures, ICRA, 2007.



Vision: Markerless Tool Tracking

- Goal: general tracking method using prior geometric model
- Approach:
 - build initial foreground/background model
 - project geometric model into image
 - “fit” projection to foreground
 - update model
- Core approach:
 - EM model building
 - MLE tracking over kinematic model

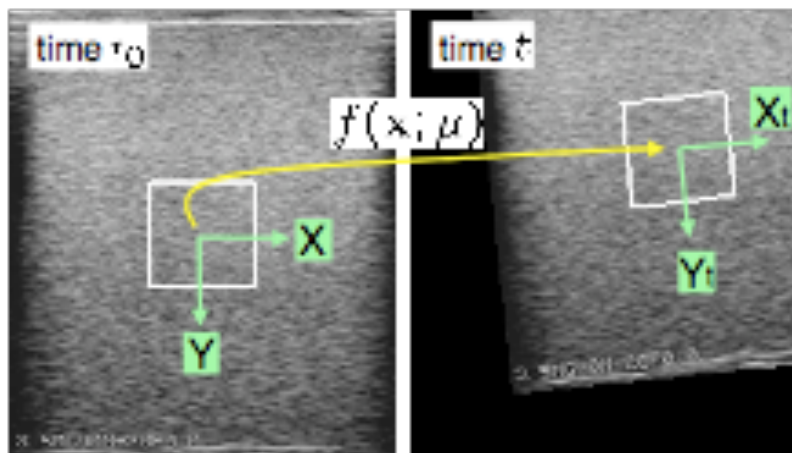


Other Realtime Imagery: Tracking in Ultrasound

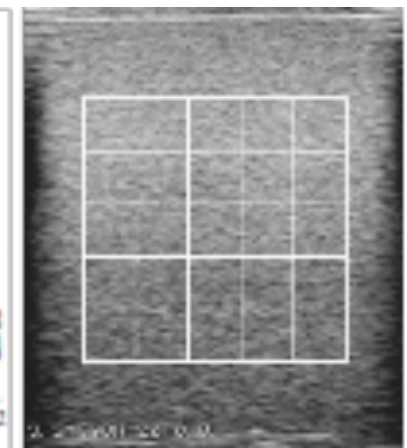
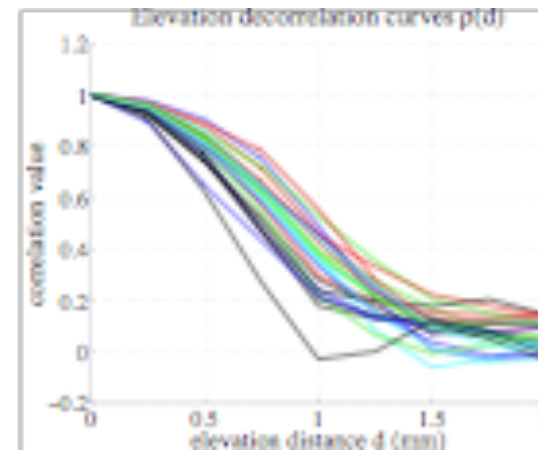
(Alexandre Kruppa, IRISA)

In plane tracking: SSD

Out of plane tracking: decorrelation

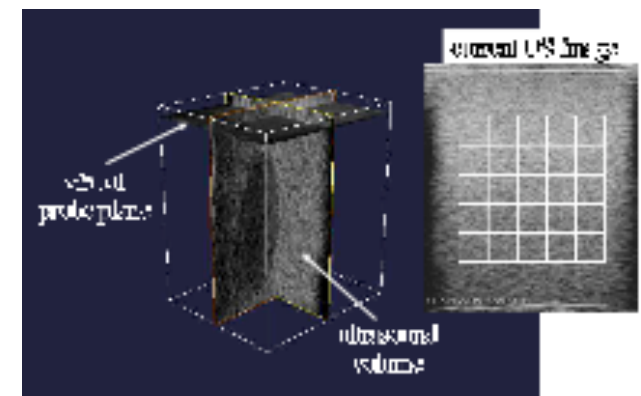


+



Result: Full 3D motion tracking about a specific point of interest

=



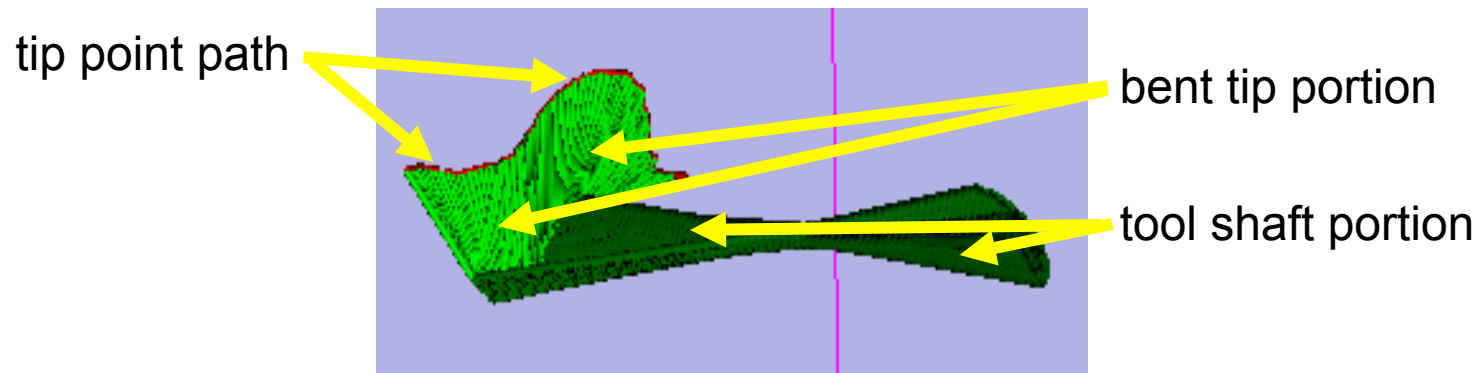
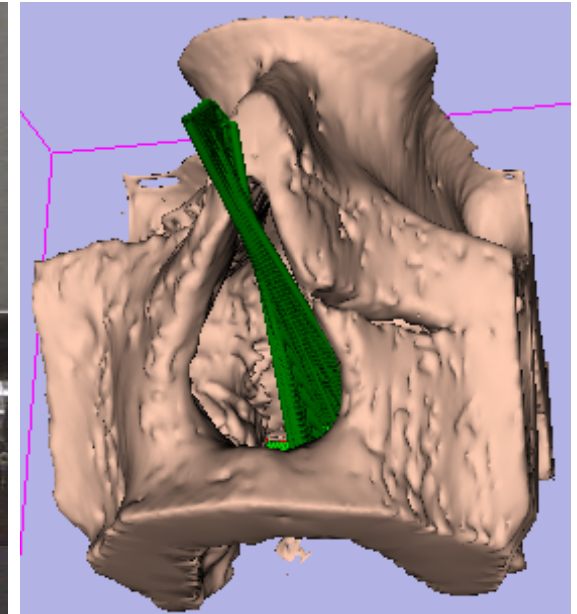
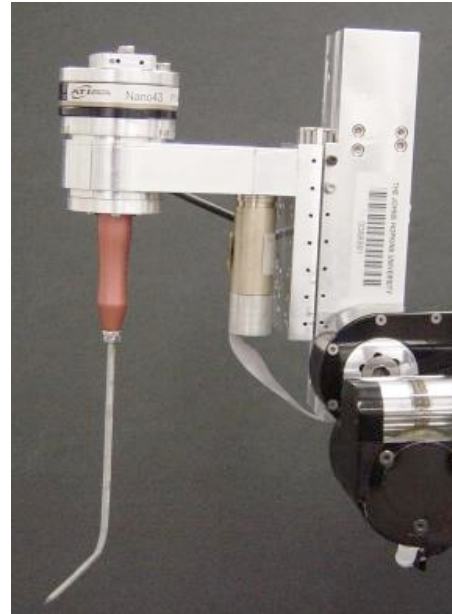
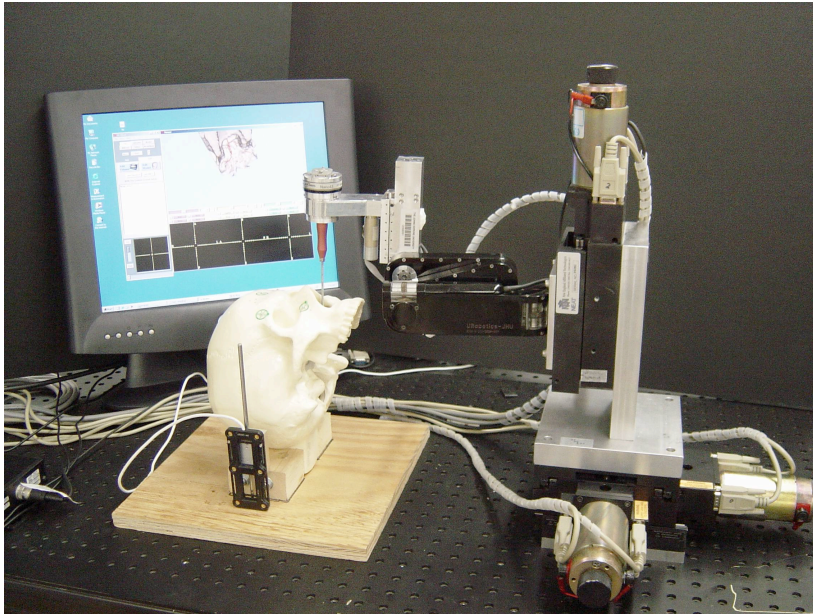
Other Realtime Imagery: Tracking in Ultrasound

(Alexandre Kruppa, IRISA)



Steady-hand sinus surgery with virtual fixtures derived from Complex Models

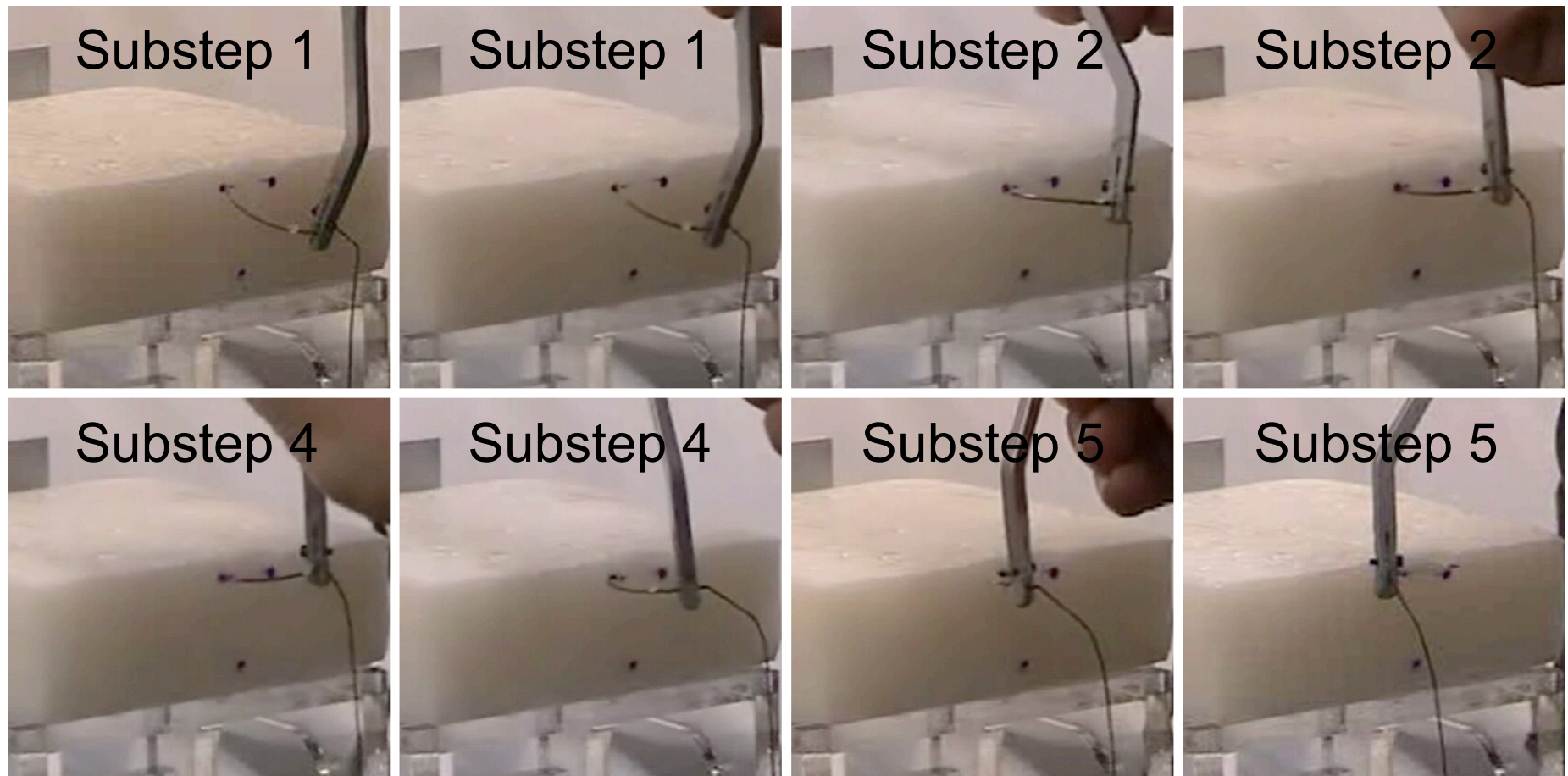
(Ming Li, Russell Taylor)



Multi-Step Procedures Virtual Fixtures for Suturing

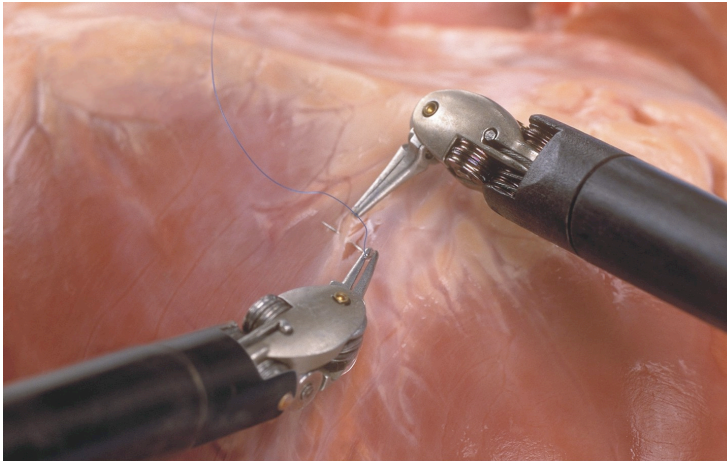
A. Kapoor, R. H. Taylor. A Constrained Optimization Approach to Virtual Fixtures for Multi-Handed Tasks. In Proceedings, IEEE International Conference on Robotics and Automation, 2007.

A. Kapoor, M. Li, and R. H. Taylor. Constrained Control for Surgical Assistant Robots. Presented at IEEE International Conference on Robotics and Automation, pp. 231 - 236, 2006.



Virtual Fixtures for Telemanipulation

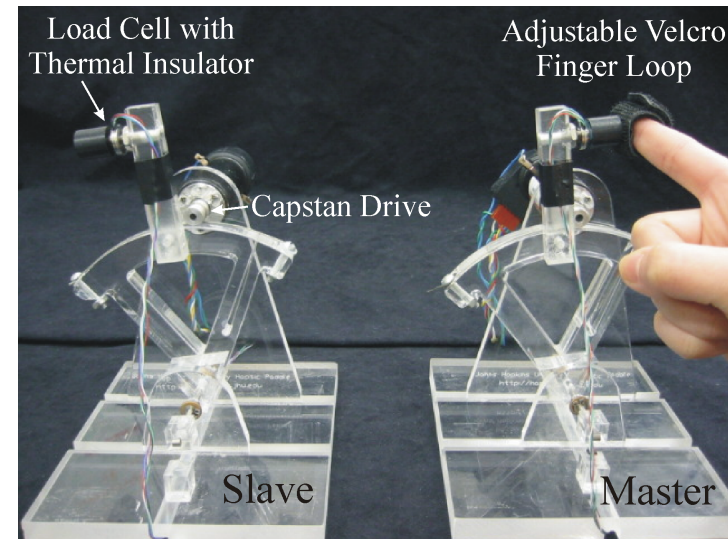
Okamura and Abbott



The da Vinci[®] Surgical System
Image courtesy Intuitive Surgical[®]



PHANTOM[®] robots configured for telemanipulation.

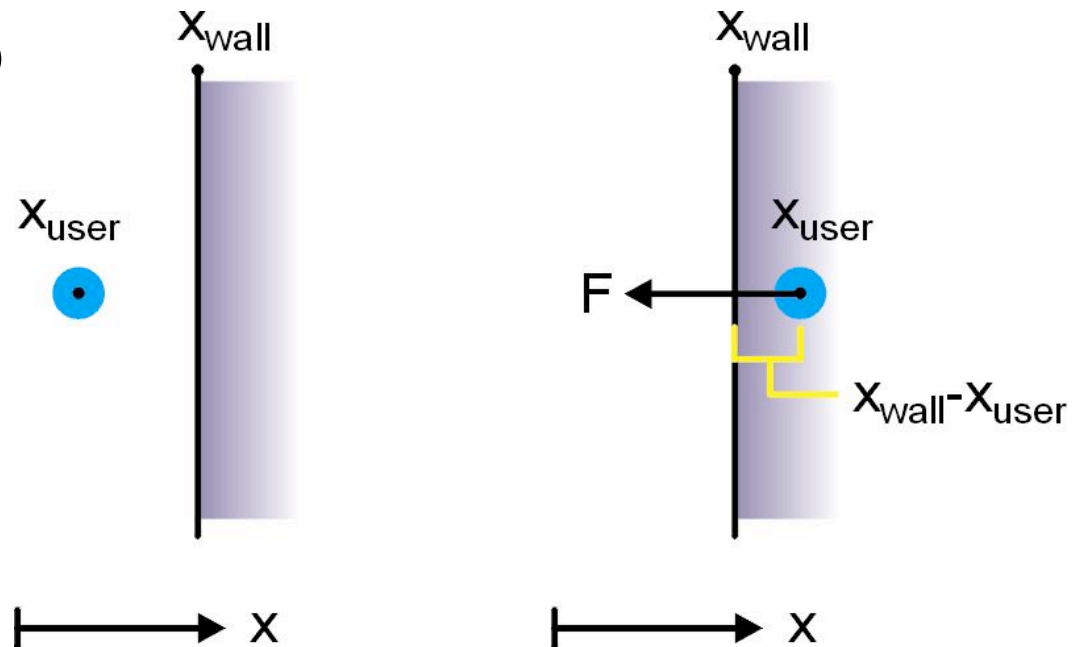


Haptic Paddles configured for telemanipulation.

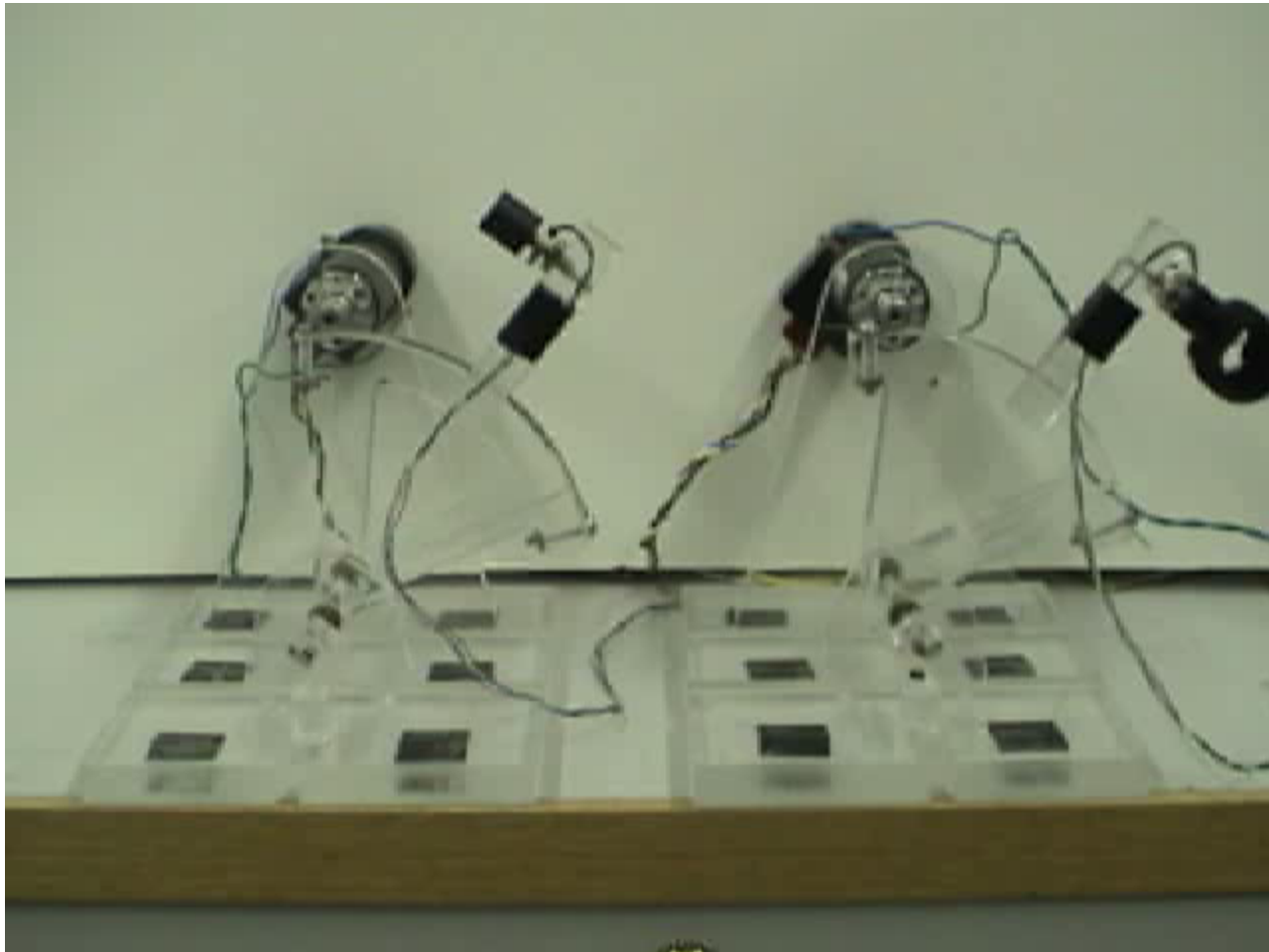
Forbidden-Region Virtual Fixtures via the Virtual Wall

The “virtual wall” is the most common building block used in constructing haptic virtual environments.

If $x_{user} > x_{wall}$, $F = k(x_{wall} - x_{user})$
stiffness $k > 0$



Unstable Virtual Fixtures

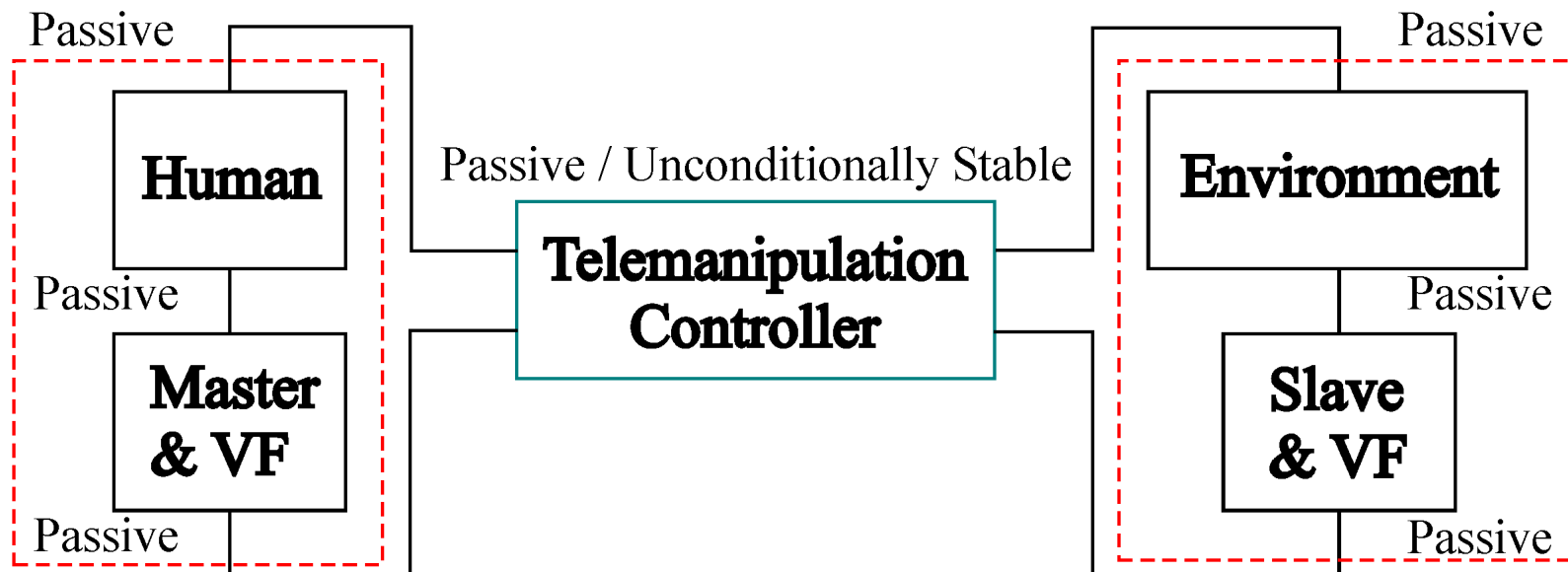


Stable Virtual Fixtures for via Passivity



Stable Virtual Fixture via Passivity

J. J. Abbott and A. M. Okamura, "Stable Forbidden-Region Virtual Fixtures for Bilateral Telemanipulation," ASME Journal of Dynamic Systems, Measurement, and Control, Vol. 128, pp. 53-64, 2006.



Including Human Dynamics

P. Marayong, G. D. Hager, A. M. Okamura. Control Methods for Guidance Virtual Fixtures in Compliant Human-Machine Interfaces. IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 1166-1172, 2008.

P. Marayong, H. S. Na, and A. M. Okamura, "Virtual Fixture Control for Compliant Human- Machine Interfaces", IEEE International Conference on Robotics and Automation, 2007. pp. 4018-24.

P. Marayong and A. M. Okamura, "Speed-Accuracy Characteristics of Human-Machine Cooperative Manipulation Using Virtual Fixtures with Variable Admittance," Human Factors, Vol. 46, No. 3, pp. 518-532, 2004.



Sensing and Visualization



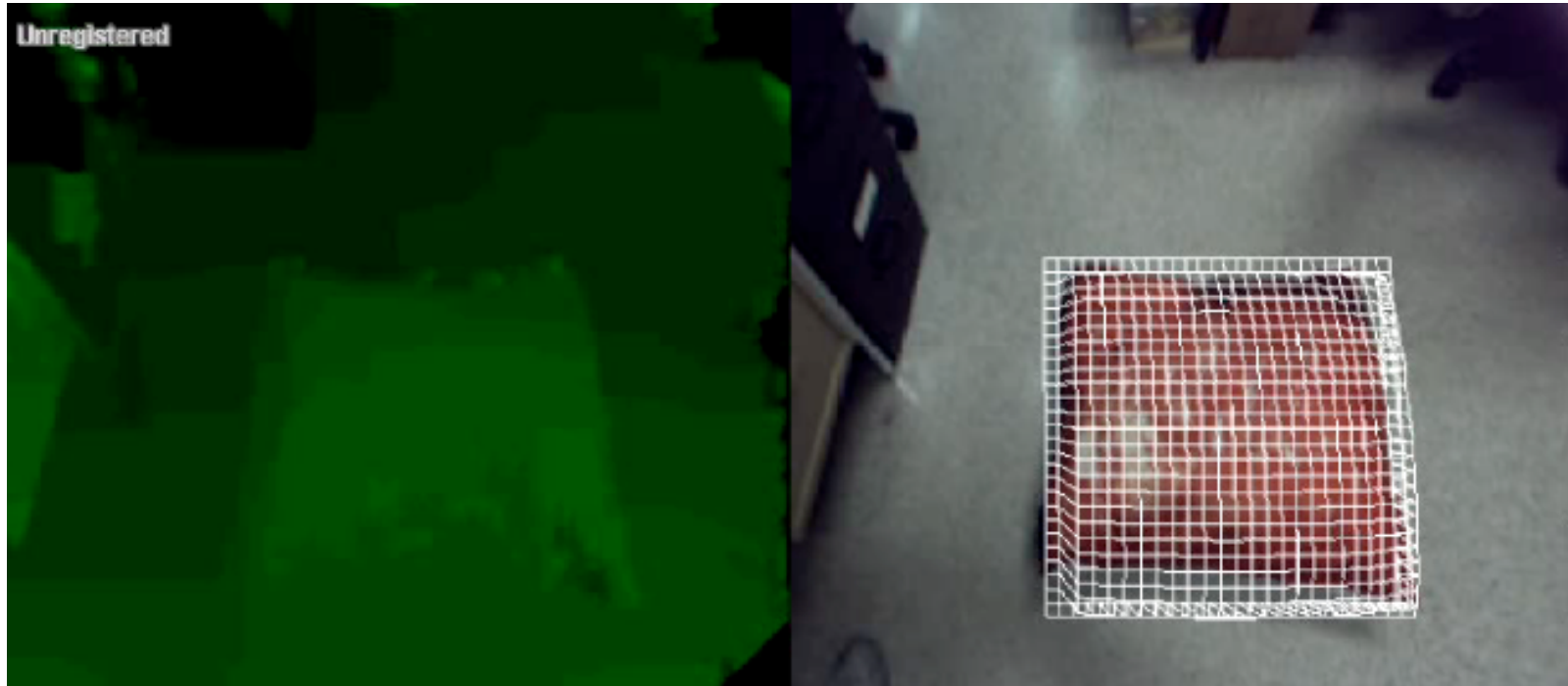
Visualization: Pre- and Intra-Operative Information Sources

- *Real-time* knowledge of
 - surgical tools
 - operative surfaces
- *Real-time* registration and visualization of
 - pre-operative images
 - pre-operative plans
 - intra-operative sensing
- *Real-time* feedback of
 - forces
 - physiological data
- MR/CT (P/I)
- Xray (P/I)
- OCT (P/I)
- Image/Video (P/I)
- Force (I)
- Ultrasound (P/I)
- Tracking systems???

Main Issue: Computing relationships with **actual** patient anatomy



New Real-Time Stereo Surface Reconstruction and Volume Registration



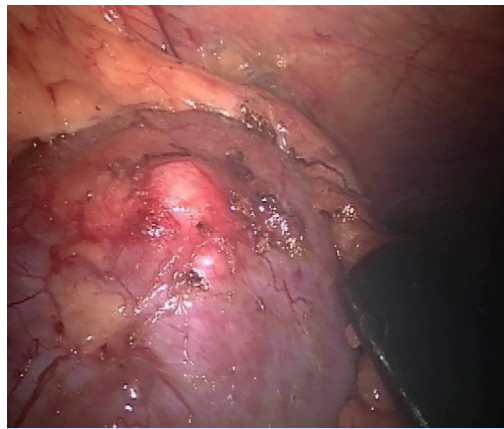
Stereo:

- Heirarchical dynamic programming
- Minor modifications for illumination

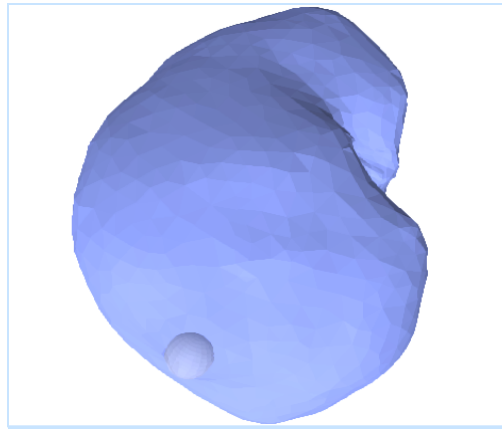
Registration:

- Surface-to-surface w/ ICP
- Adding deformation and use of surface features

CT Registration To Live Stereoscopic Video

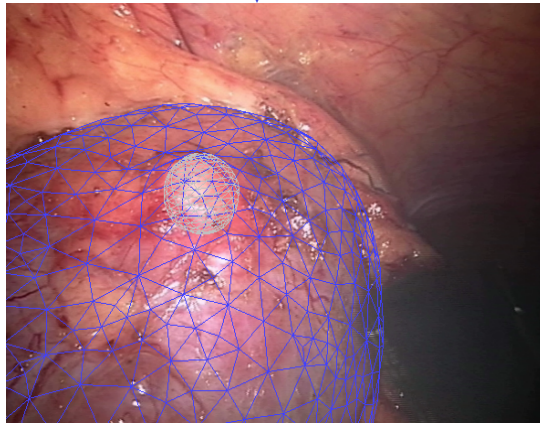


original stereoscopic video

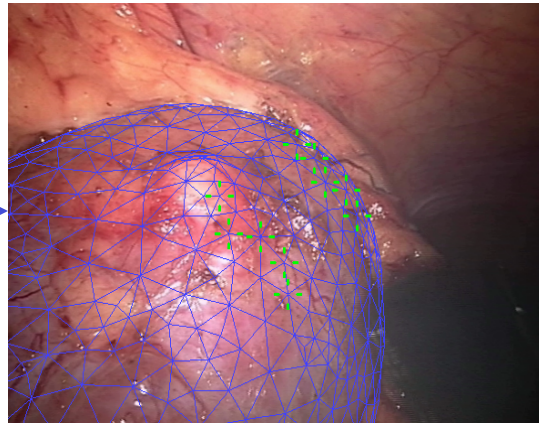


CGI of the segmented kidney

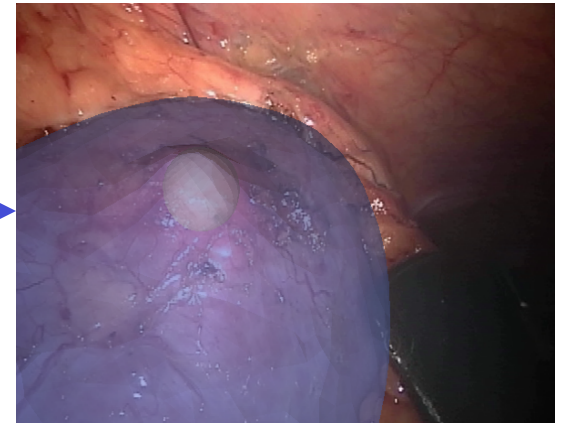
merged



Overlay after manual registration



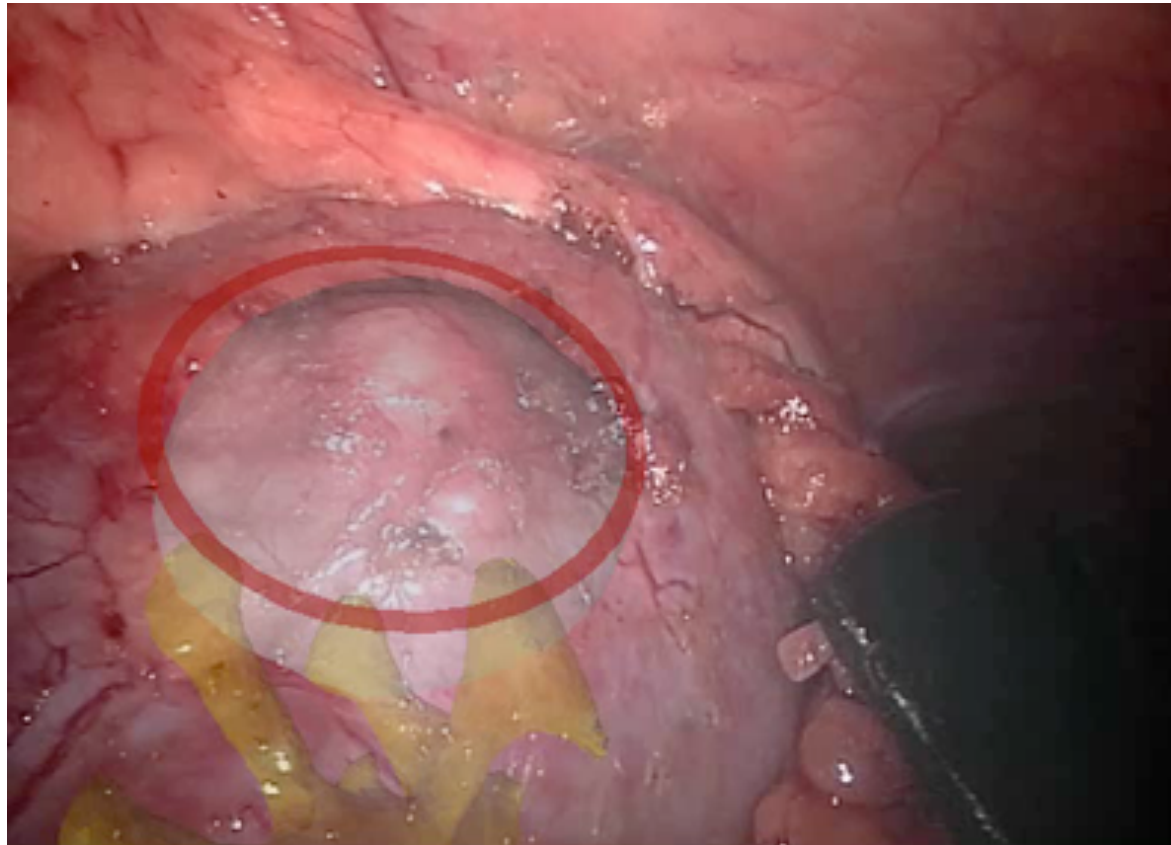
Target selection for tracking



Registered final product

CT Registration To Live Stereoscopic Video

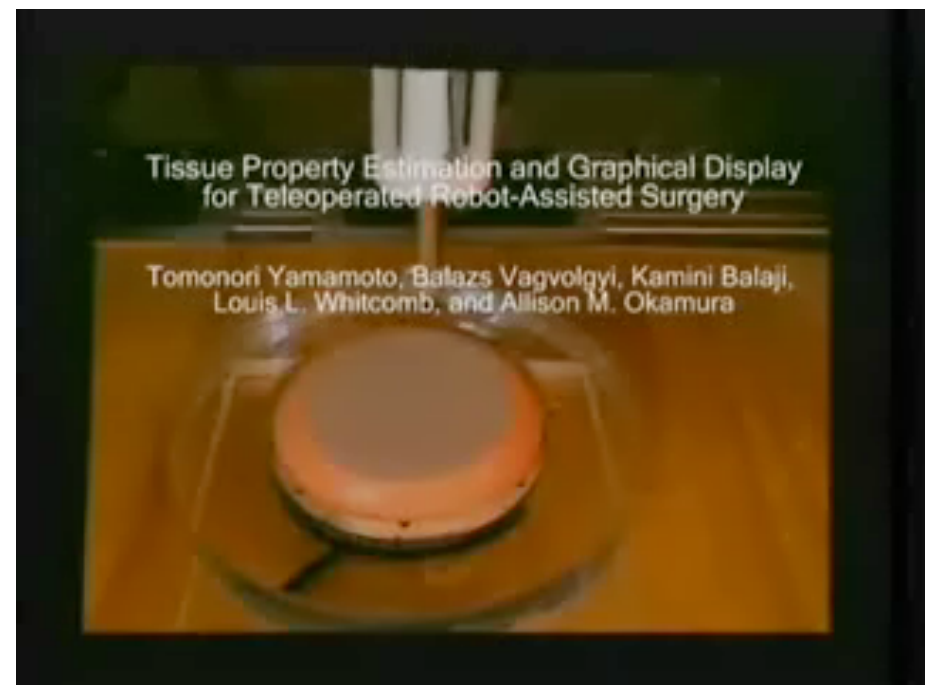
Automatic Tracking & Registration



Real-time importation and display of preoperative information in
in the surgeon field of view

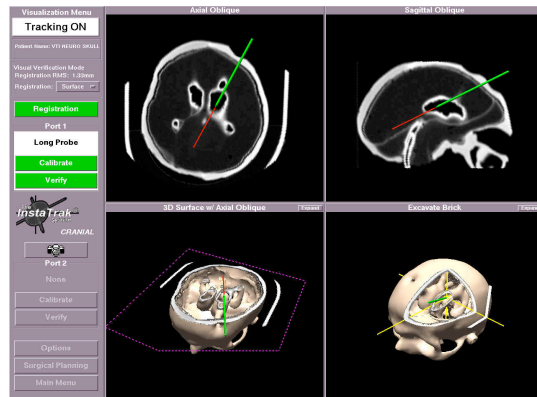
And now, the same for forces

- Compute tissue stiffness using measured forces
- Display stiffnesses on surface
- Maintain registration using previous registration methods

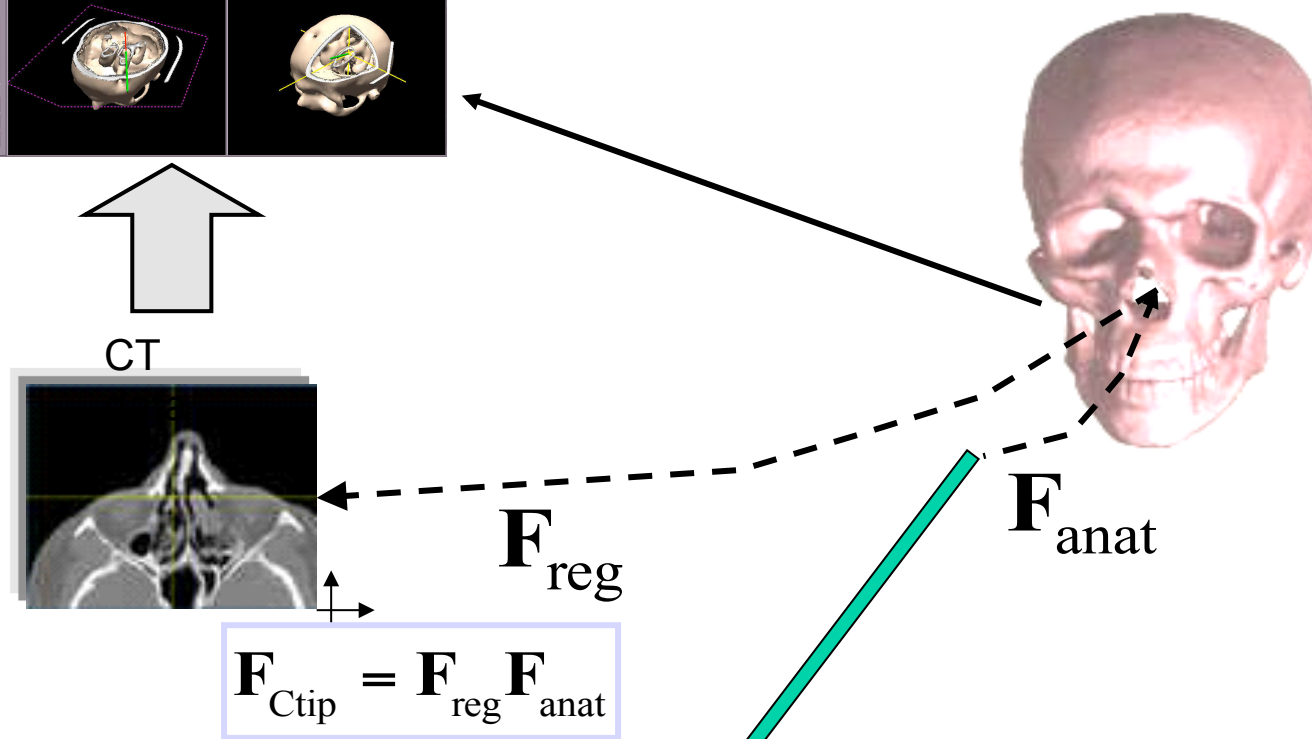


Dynamic Direct Registration

Come to our oral presentation Monday afternoon for details!

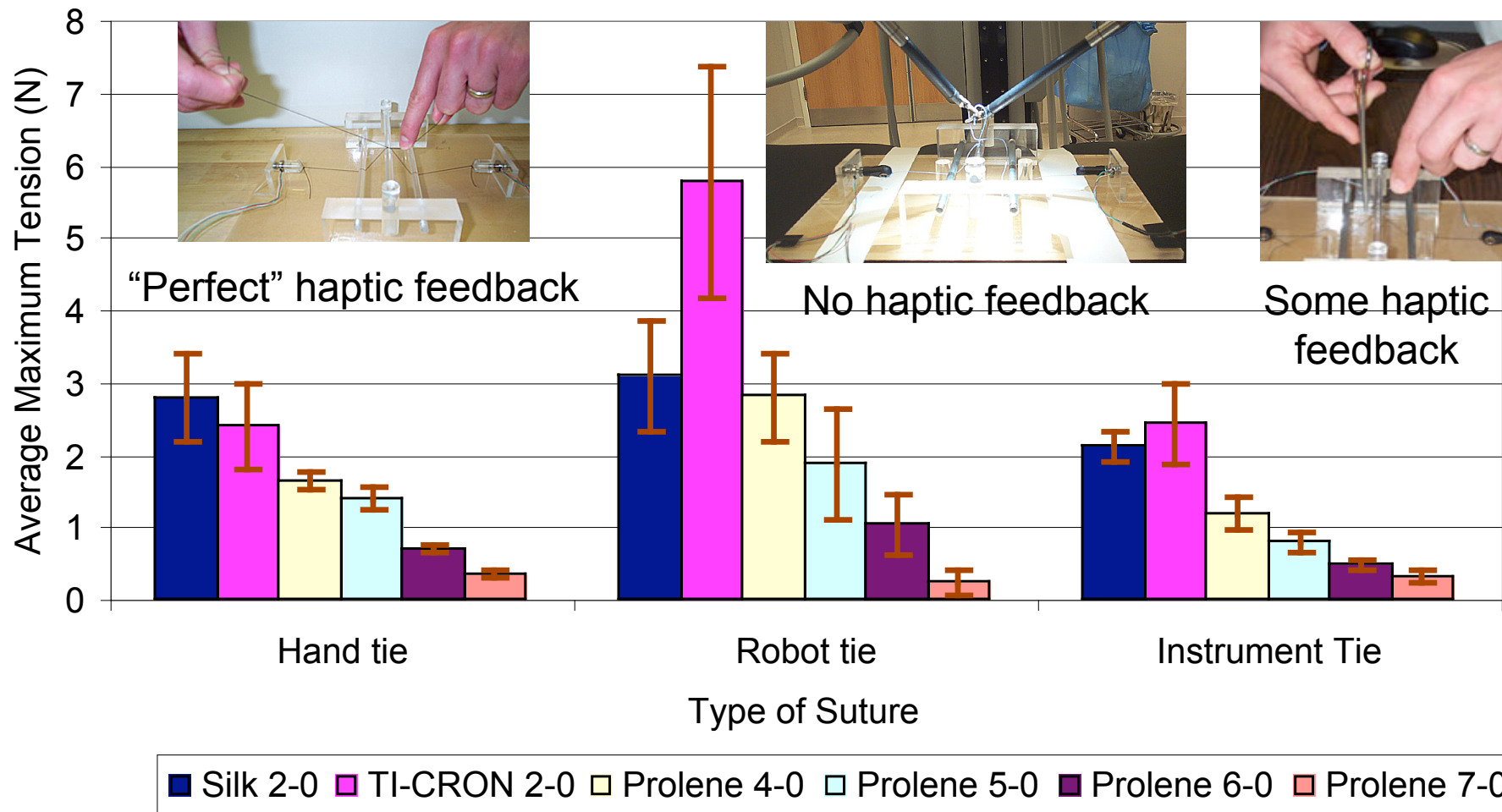


From a sequence of intra-operative images, compute registration to pre-operative data (and surgical tools)



The Need for Haptic Feedback

(Okamura, Abbott, Marayong)



Data summary for a single subject (attending surgeon). The forces applied to various sutures change with suture strength. For this subject, the instrument tie force levels and standard deviations of the hand tie and instrument tie are similar, while those of the robot tie are different.

Engineering Research Center for Computer Integrated Surgical Systems and Technology

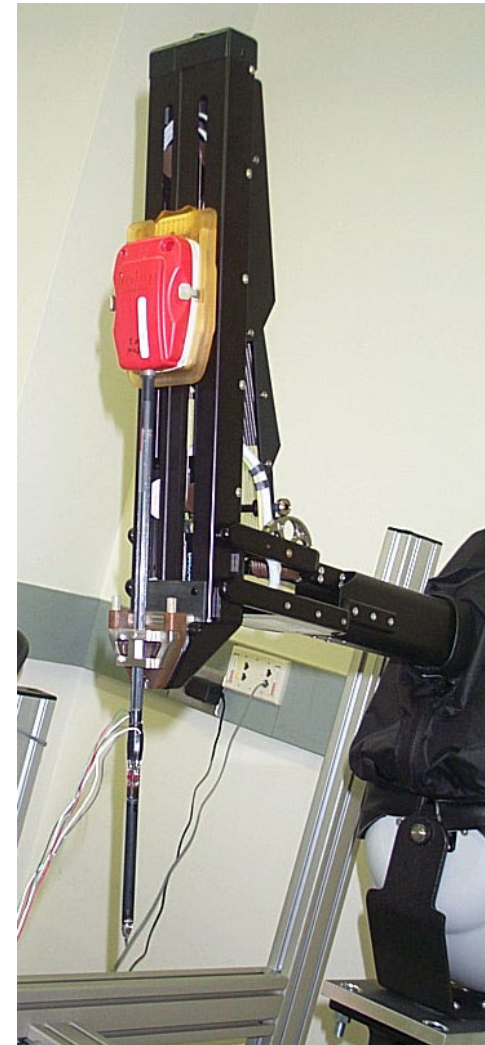
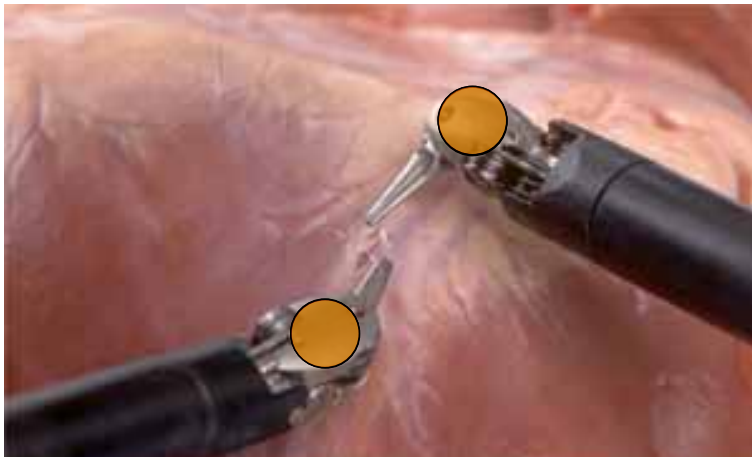
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Augmented Reality for Surgeon Assistance

T. Akinbiyi, A. Okamura, D. Yuh

- Force sensors in robotic surgical instruments
- Computer display of warning when force is too high
- Pilot study for suturing
 - 3:1 reduction in broken sutures



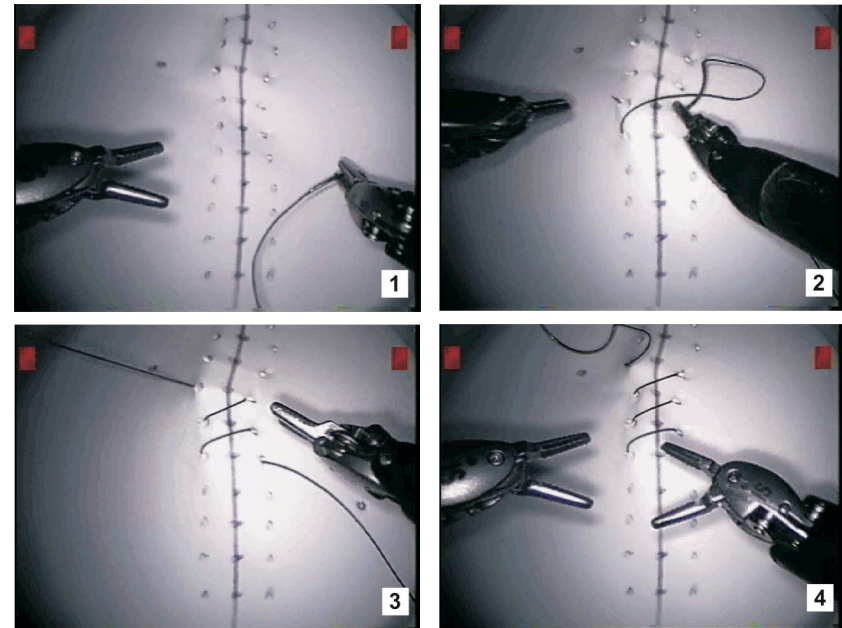
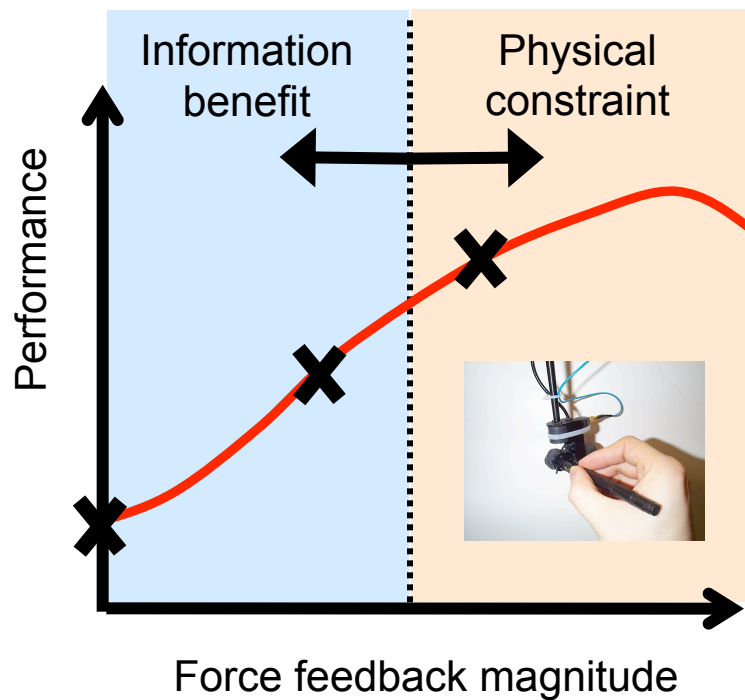
Modeling the Human Element



Human Modeling

Fundamental research on human modeling for learning and effectiveness is needed

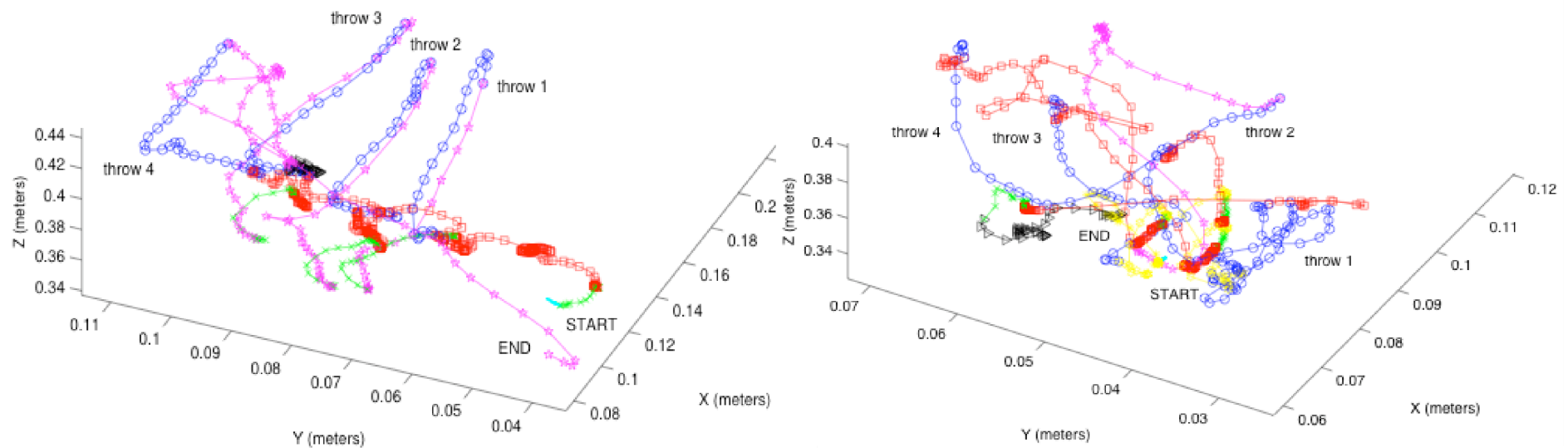
Increased force feedback provides increasing performance benefit



Studies of surgical learning curves require task modeling and human motion recognition

Context Aware Surgical Assistance

- Develop methods for observing and understanding surgery and surgical technique



Two examples of a 4-throw suture

What Can We Do With This?

- Label two different suturing trials with the automatically derived surgemes
- Align the two trials using ``edit distance’’
- See how much and where they match
 - Experts differ less from each other than they do from intermediate or novices

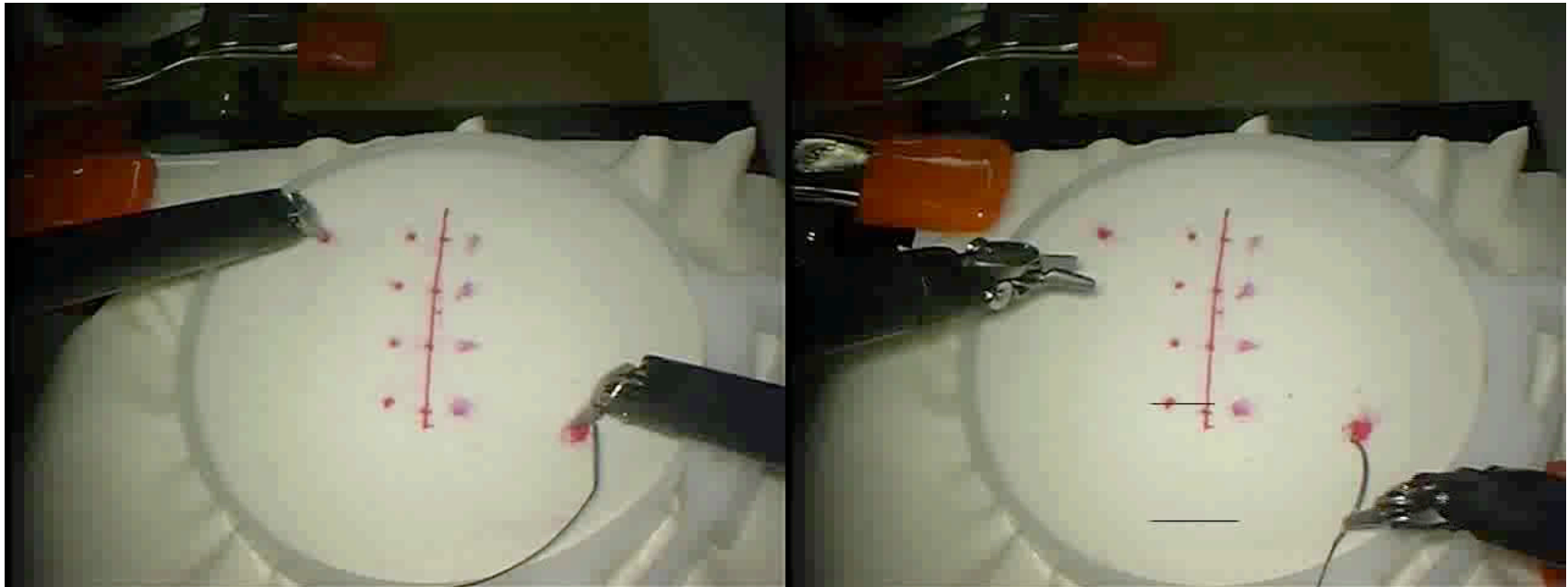
	Experts	Intermediate	Novices
Experts	38%	51%	61%
Intermediate	51%	42%	62%
Novices	61%	62%	65%



Expert-Expert



Expert-Novice



Summary: Observations and Issues

- The right combination of hardware and algorithms is procedure dependent
 - Many of the basic design ideas are there
 - Many of the basic algorithm ideas are there
 - There is **huge** value in their customization
 - Tools like the JHU Surgical Assistant Workstation (JHU-SAW) system are a step toward standardization
- There are many open problems:
 - Development of endpoint sensing integrated with tools
 - Development of real-time anatomic measurement and registration
 - Development of context-dependent assistance methods



Some Further References

P. Kazanzides, G. Fichtinger, GD Hager, AM Okamura, LL Whitcomb, and RH Taylor. *Surgical and Interventional Robotics-Core Concepts, Technology, and Design*. Robotics & Automation Magazine, IEEE, 15(2): 122-130, 2008.

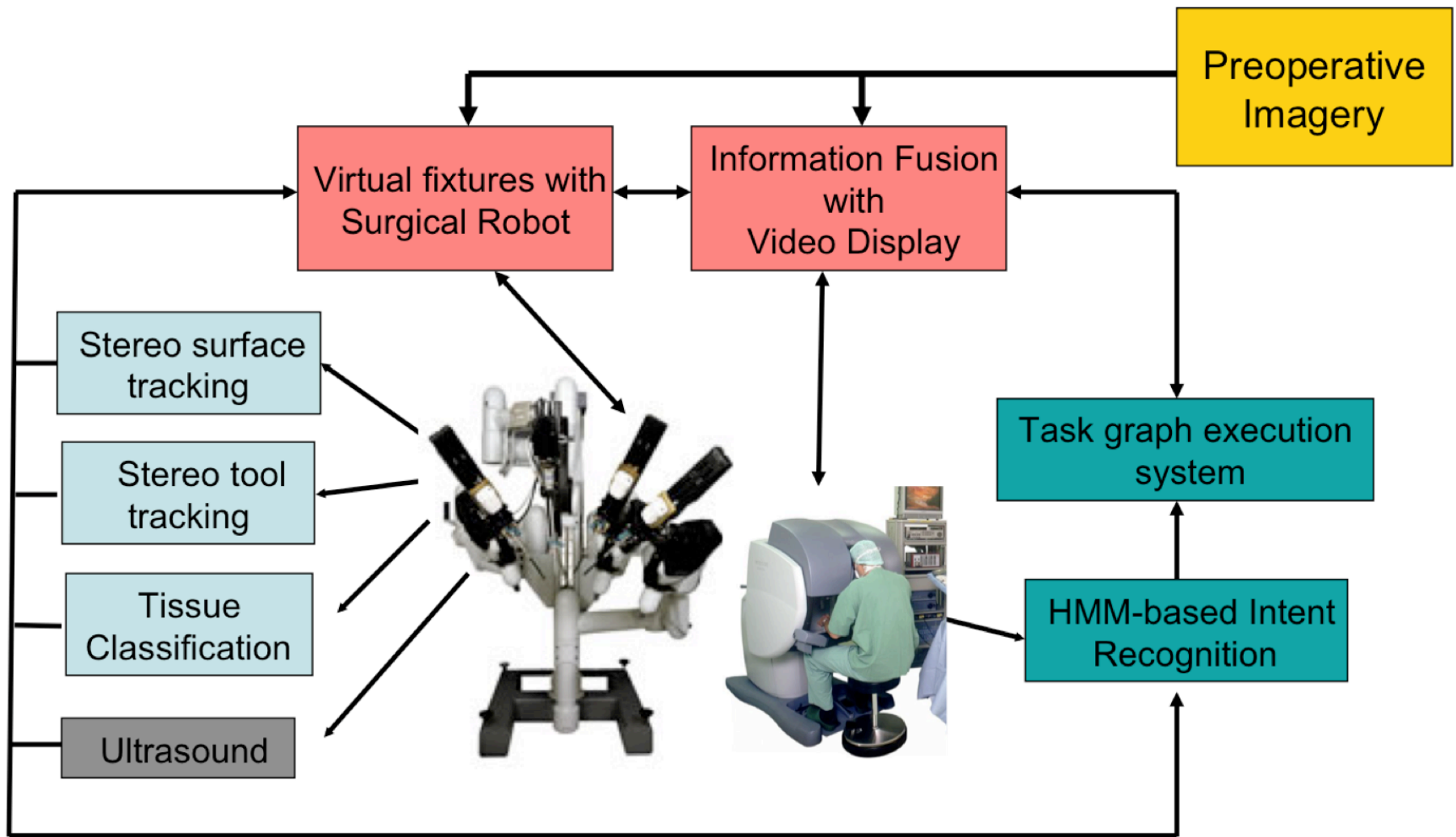
G. Fichtinger, P. Kazanzides, AM Okamura, GD Hager, LL Whitcomb, and RH Taylor. *Surgical and interventional robotics: Part II*. Robotics & Automation Magazine, IEEE, 15(3):94-102, 2008.

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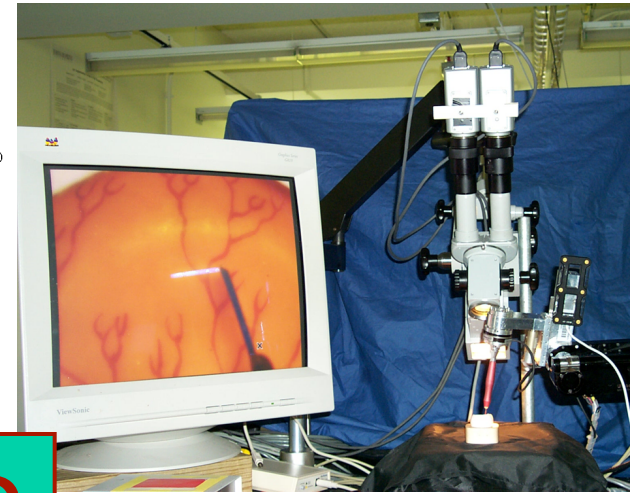
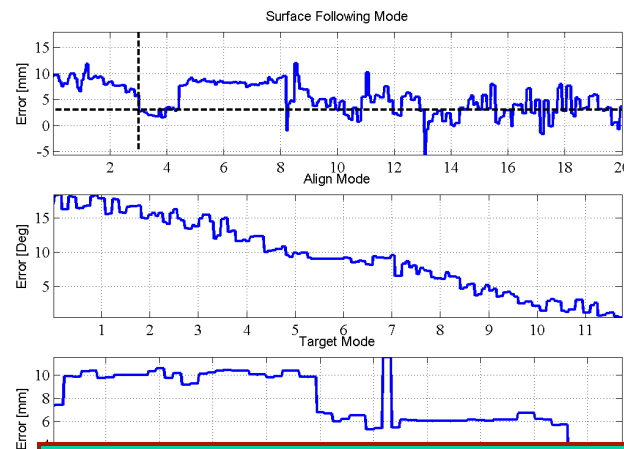
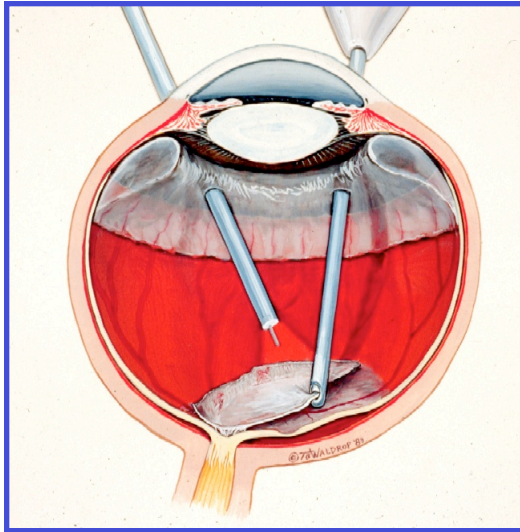
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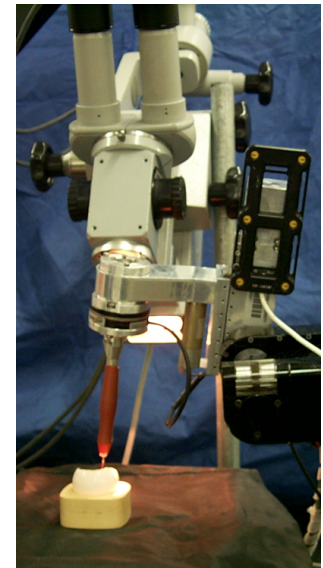
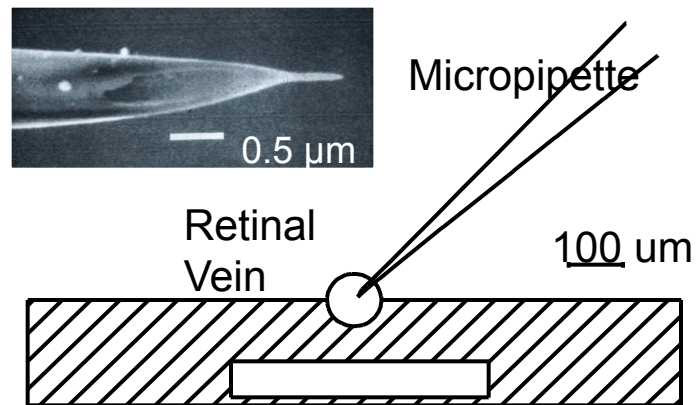
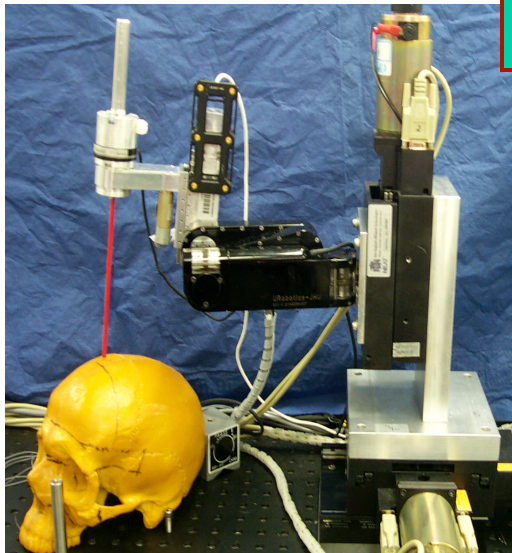
These notes will be posted at
<http://www.cs.jhu.edu/~hager/Public/MICCAI-Tutorial.pdf>



Thanks...



Questions?



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