An Overview of the Telesurgical Workstation Project

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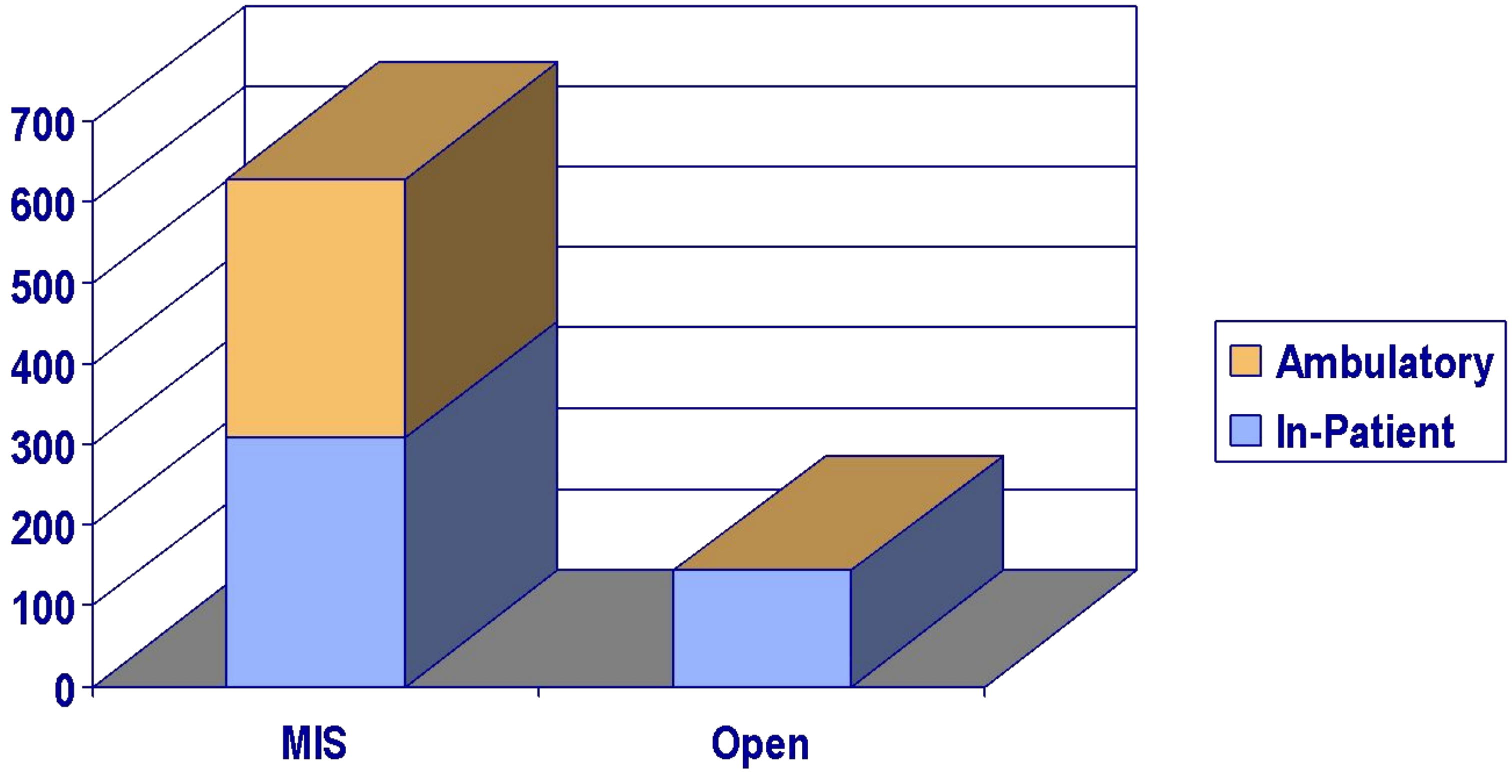
Minimally Invasive (MIS) Vs. Open Cholecystecomies (Thousands, U.S., 1996)



> 80% Cholecystecomies done with MIS!
(likewise for many other surgeries)

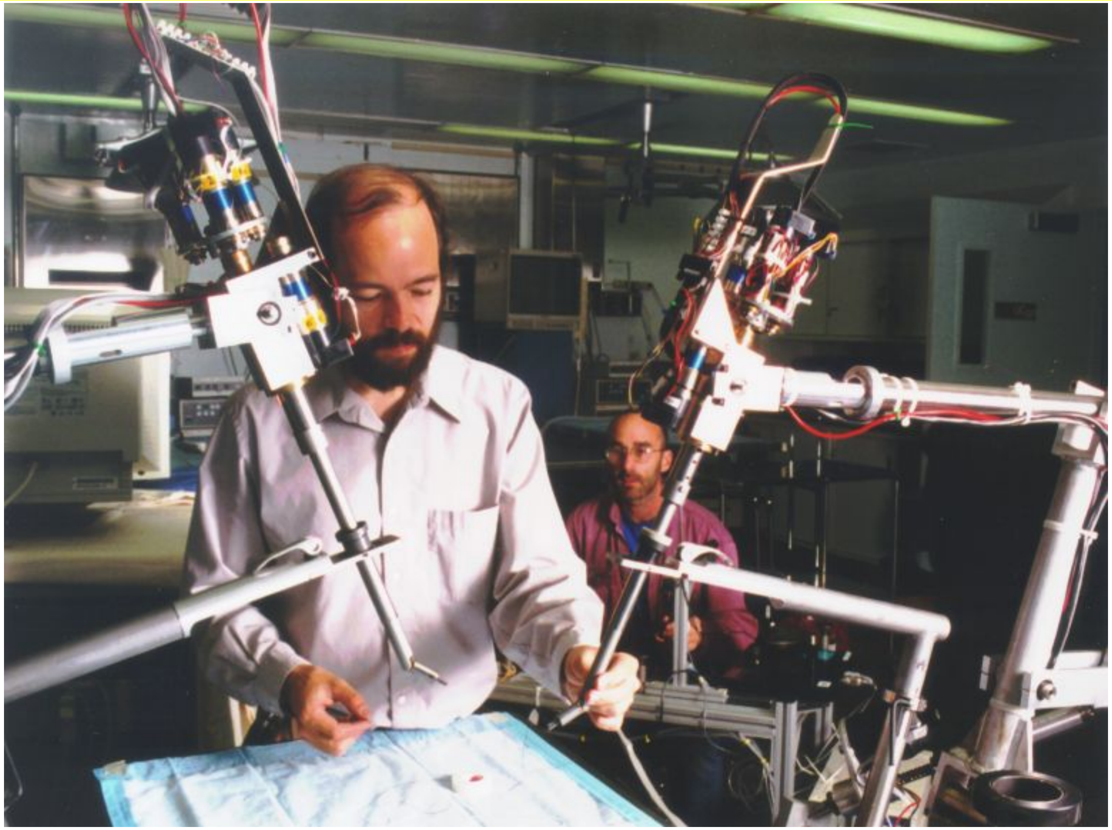
Minimally Invasive Surgery

- Operations through small incisions
- Reduced trauma to healthy tissue
- Less pain, shorter hospital stay, and reduced cost
- More difficult techniques due to reduced access, dexterity, and perception
  - Limited dexterity due to 4 DOF available
  - Reduced force feedback
  - No tactile feedback
  - Reduced hand-eye coordination
  - Problems in spatial planning
- Many procedures cannot be performed with current MIS technology or are extremely difficult

Overcoming M.I.S. Limitations

- Replace the surgical instruments with robotic manipulators controlled by the surgeon through teleoperation
- Increase dexterity by added DOF

Minimally Invasive Robotic Surgery



U. C. Berkeley, UCSF Bimanual Telesurgery Test-Bed

Winthrop T. Williams, Dmitry Derevyanko, Matt Danning,

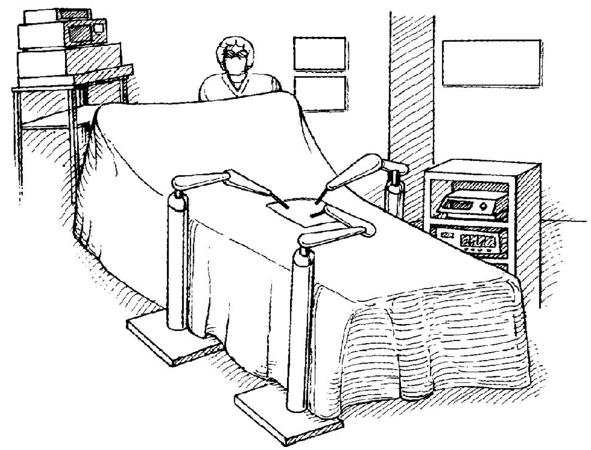
M. Cenk Cavusoglu, Michael Cohn, S. Shankar Sastry

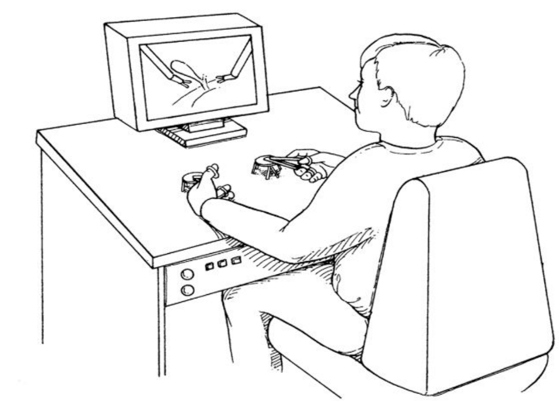
Outline

- UCB/UCSF Laparoscopic Telesurgical Workstation
  - Minimally invasive surgery and telesurgical system concept
  - Design of UCB/UCSF telesurgical workstation
  - Bilateral controller design for high fidelity teleoperation
- Surgical Training Simulator
  - Current practice in surgical training and VE based training
  - Haptic interfacing to virtual environments

Telesurgical System Concept

- Replace the surgical instruments with robotic manipulators controlled by the surgeon through teleoperation
- Increase dexterity by added DOF, improved perception through force and tactile feedback





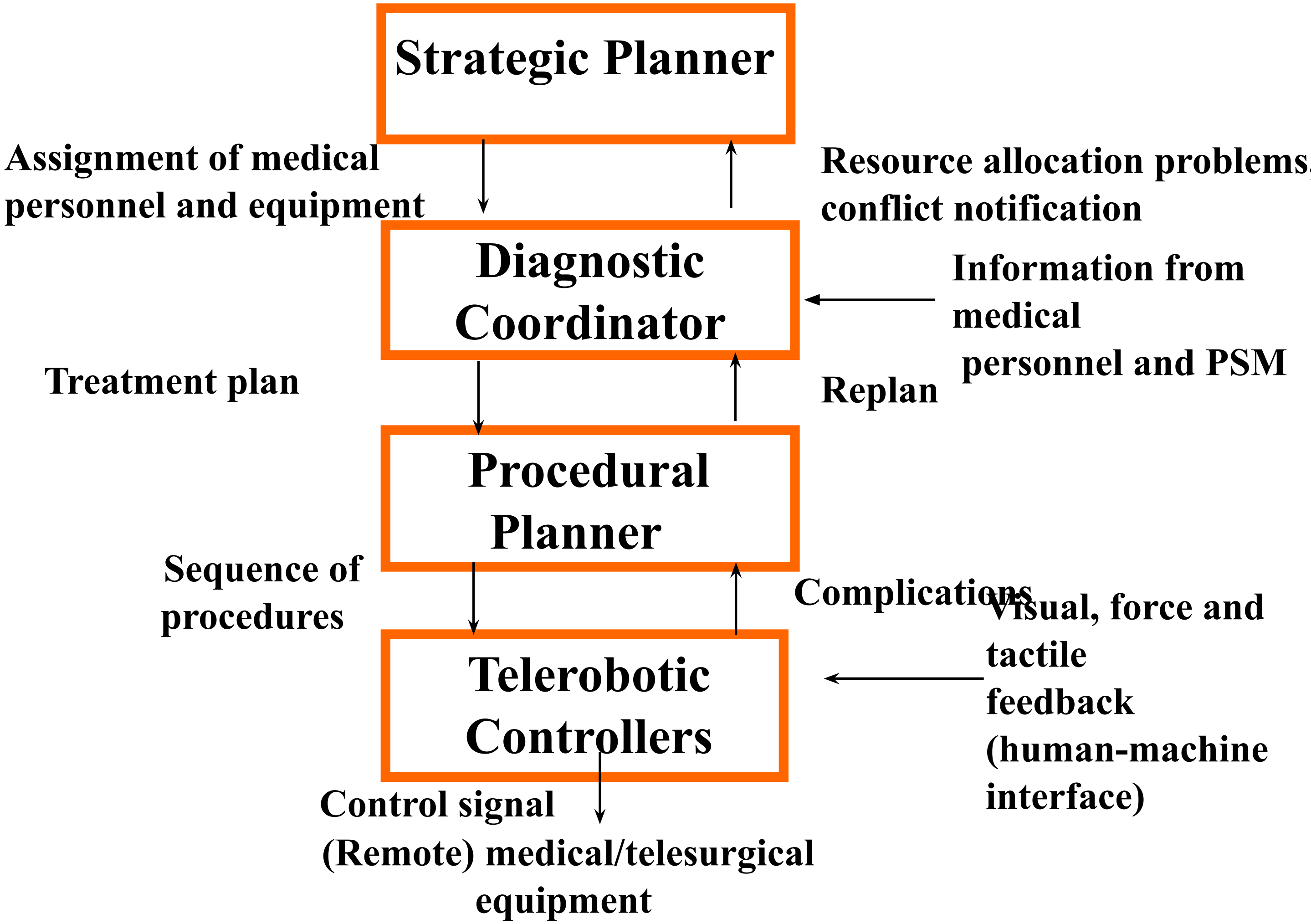
Program Plan

- Our research objective is the development of improved tools for endoscopic manipulation, sensing and human interfaces for a teleoperative surgical workstation
- These tools could be used within the operating room or remotely for procedures in hazardous environments such as the spacestation, minefields, battlefields, etc.
- Our telesurgical workstation incorporates two robotic manipulators with dexterous manipulation and tactile sensing capabilities, master devices with force and tactile feedback, and improved imaging and 3D display systems, all controlled through computers
- Virtual reality training simulator for minimally invasive surgery

Scenario

- The telesurgical workstation is a teleoperation system
- The surgeon is physically remote from the operation site and interacts through manipulators and video display
- Surgical operations are performed with minimally invasive technique—insertion of instruments and viewing equipment into the body through natural orifice or punctures created by a the surgeon
- Desired performance is achieved by the master-slave control algorithm
- Design of model-based algorithms for bilateral master-slave teleoperation with force feedback
- Telesurgery techniques can be taught on a virtual reality training simulator

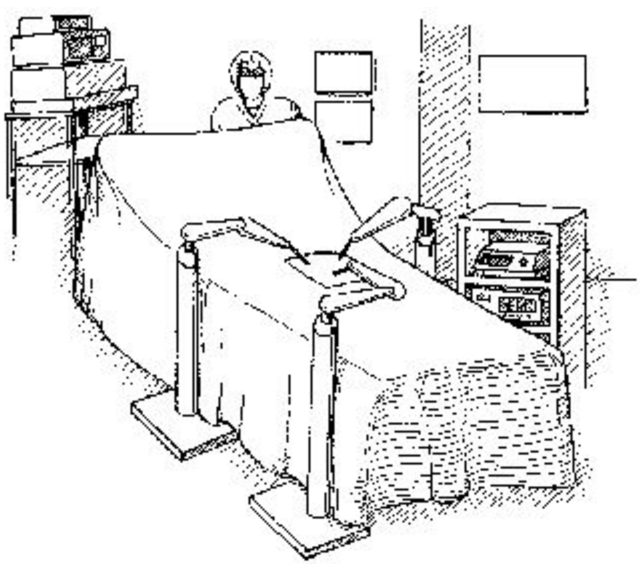
Intelligent Medical Care Delivery Systems

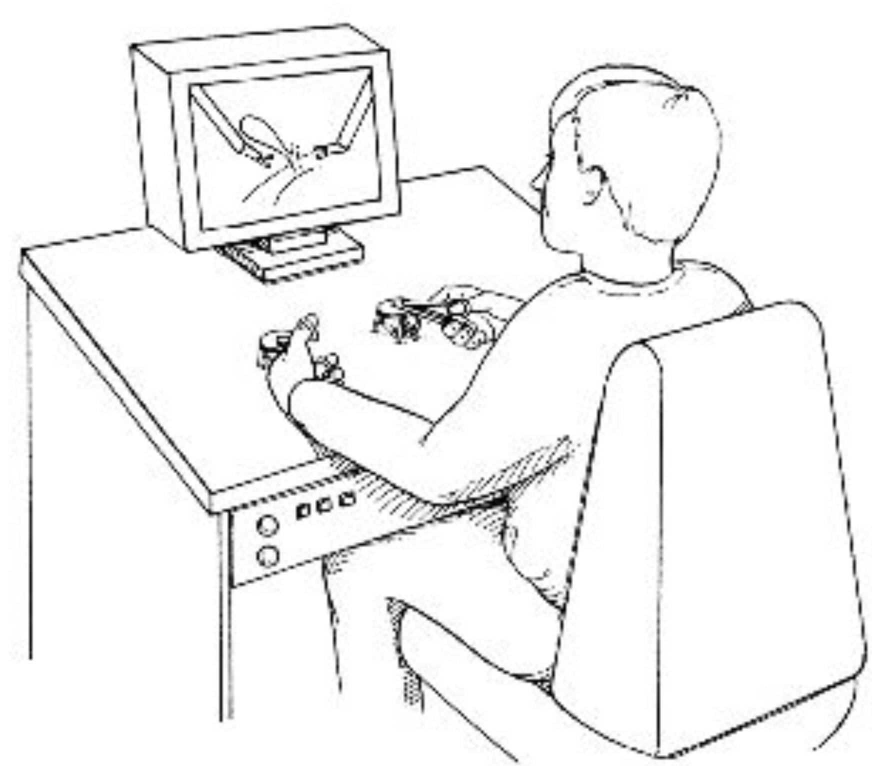


Research Team: UCB & UCSF

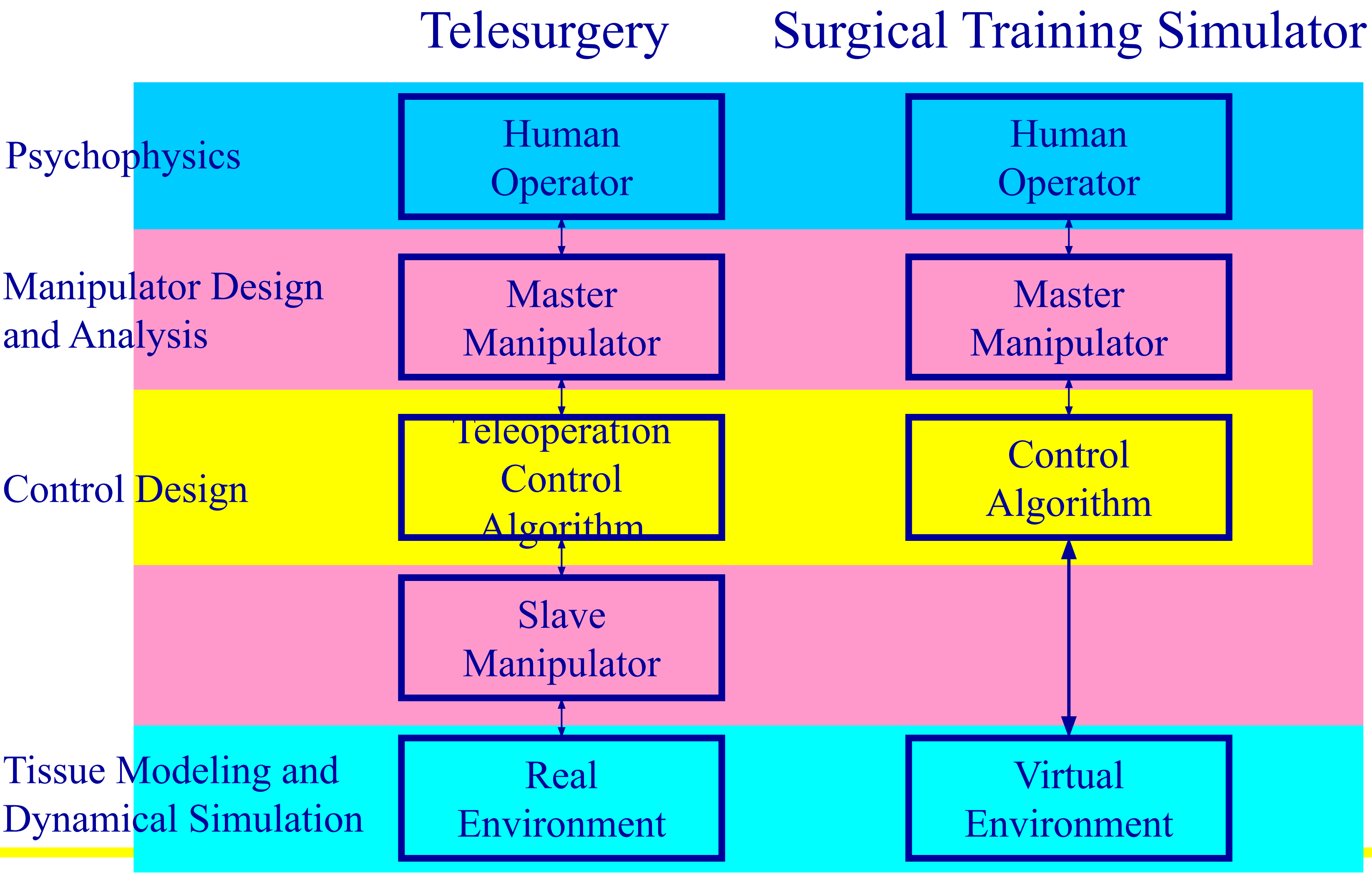
- UCB Engineering team (Sastry, Fearing) areas of expertise
  - Creation of algorithms for efficient real-time modeling of deformable bodies
  - Multi-modal visualization with registration of video image
  - Wireless communication and networking
  - Stereoscopic and volumetric display of real and virtual images
- UCSF Department of Surgery team (Tendick, Way) areas of expertise
  - Laparoscopic and endoscopic surgical techniques and procedures
  - Modeling of soft tissue behavior for simulation
  - Methods for training motor and spatial skills using virtual environments

Teleoperation with Force Feedback and Stereo Teletaction





Overview

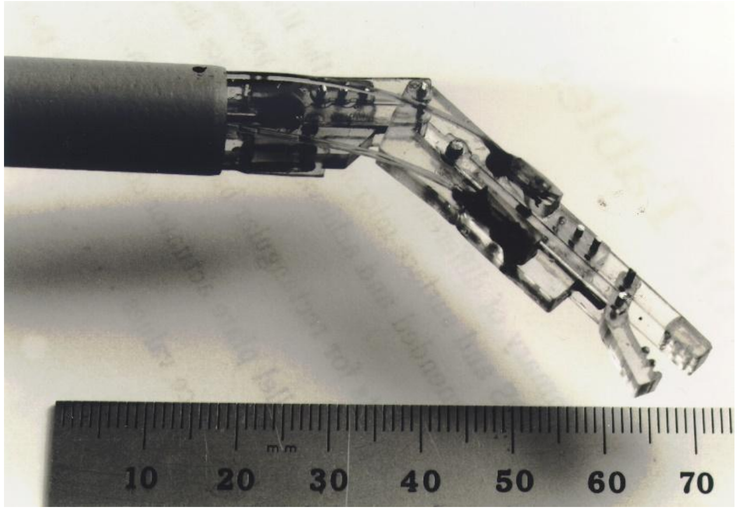


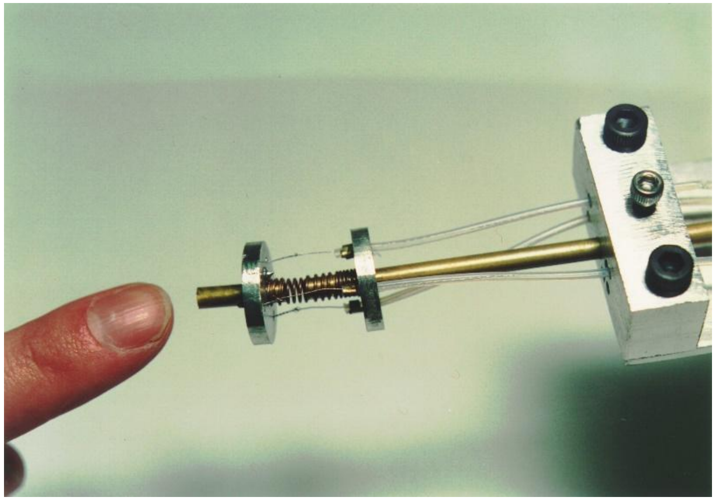
Telesurgery
Surgical Training Simulator
Psychophysics
Human Operator
Human Operator
Manipulator Design and Analysis
Master Manipulator
Master Manipulator
Control Design
Teleoperation Control Algorithm
Control Algorithm
Slave Manipulator
Tissue Modeling and Dynamical Simulation
Real Environment
Virtual Environment

Telesurgical Workstation

- Robotic platform provides global positioning for the millirobotic manipulator
- Augmented reality, with the superposition of 3D computer graphics data reconstructions onto real-time video images can aid the surgeon in “seeing” structures beneath the surface (such as tumours)
- Stereo teletaction: two-handed interaction with force feedback
- Low-latency, low-error rate wireless communication for remote operation
- Distributed database access to medical records, digital libraries, with real time QoS

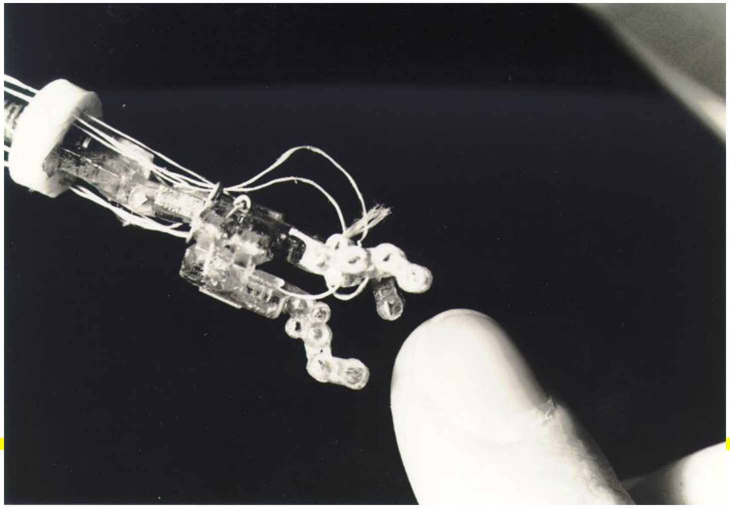
Early Work





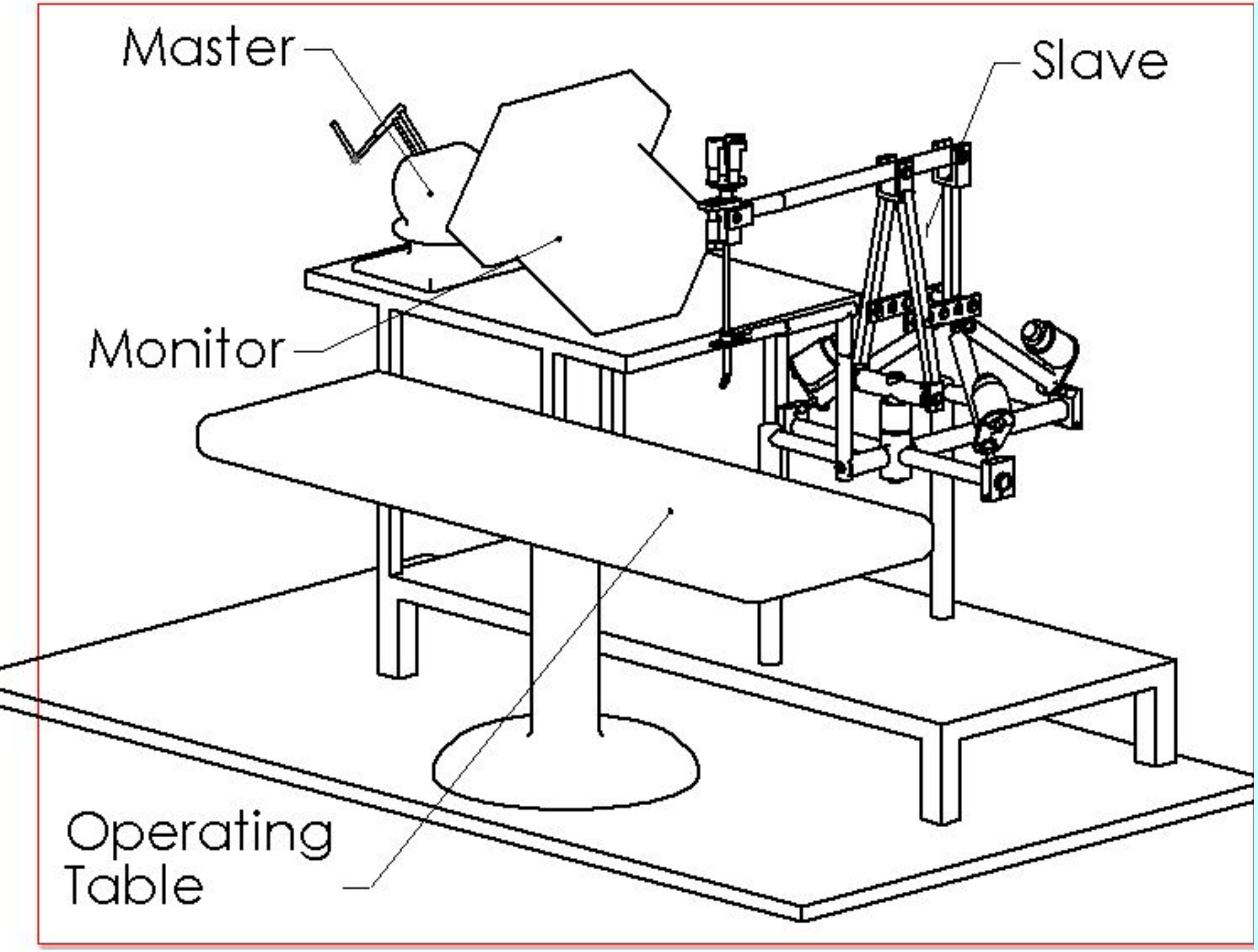
5 DOF

Integrated
Yaw & Pitch
(Single Joint)



Multi-Fingered Hand

Telesurgical Workstation: Schematic



TELESURGERY TESTBED

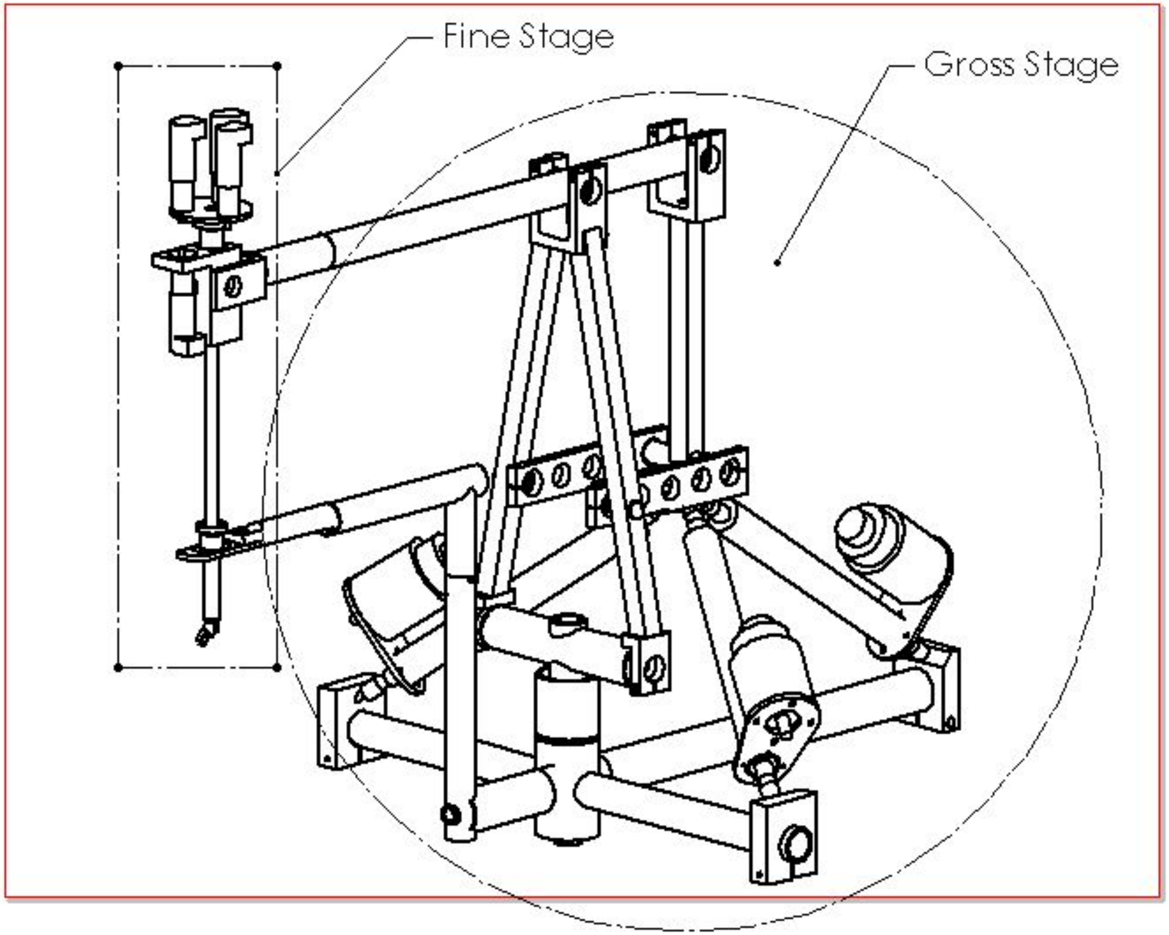
Two sub-systems:

- **Surgeon Station**
  An off-the-shelf six degree of freedom haptic interface, with three channels of force-feedback
- **Surgical Robot**
  A computer, a console, indicator lamps, amplifiers, a watchdog safety circuit, a start/stop control for the robot, and a robotic manipulator.

- The surgeon interacts with the master
- The robot interacts with the patient
- The mater is connected to the robot via a serial cable
- The robot's job is to operate the robotic manipulator as commanded by the master

While viewing the laparascopic monitor, the surgeon moves the master's stylus, thereby positioning the slave robot.

Surgical Robot



ROBOTIC MANIPULATOR

- **Gross stage**
  Consists of a trio of linear ball screw actuators and a set of linkages, including a boom, which forms a pantograph. The boom carries the fine stage.

- **Fine stage**
  Consists of an instrument shaft, wrist, gripper, and a fine stage motor group; and passes through a cannula which acts as a fulcrum so that when the ball screw actuators are commanded to a particular position, the instrument will follow.

- **Wrist and gripper**
  Orientation of the wrist is controlled by the fine stage motor group--the gross rotation motor causes the instrument shaft to rotate about its long axis. The yaw motor and roll motors work in unison to cause the wrist to bend about an axis perpendicular to the instrument shaft, and to rotate the gripper about an axis determined by the yaw angle. Attached to the end of the wrist, the gripper closes pneumatically, and is opened by a spring.

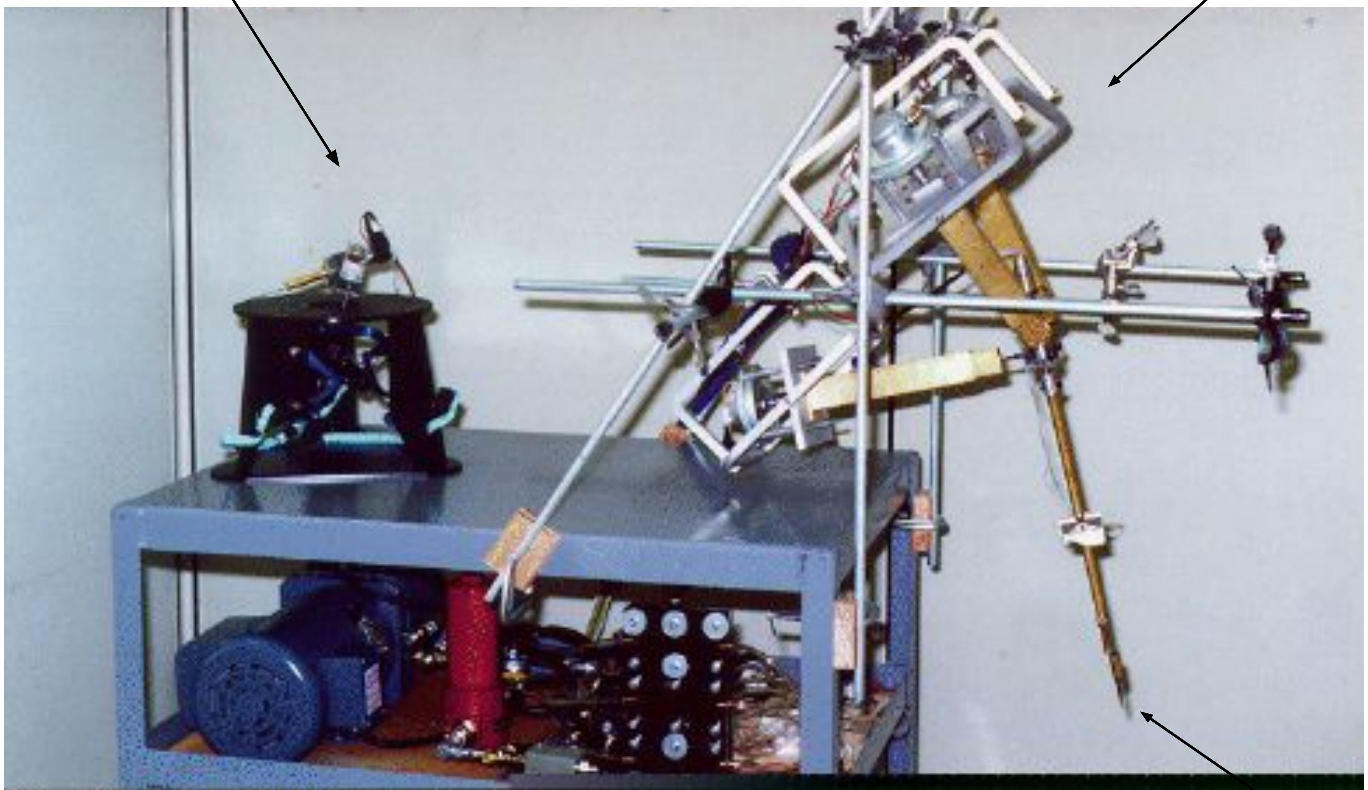
Laparoscopic Manipulators

- Our current laparoscopic manipulator design is composed of two stages. The first stage is for gross positioning of the end effector. It is a Stewart platform-like parallel manipulator, driven by electric motors, giving 4 degrees of freedom. The second state is the 3 DOF millirobot. It has a 2 DOF wrist and gripper, driven by hydraulic actuators. The design of the millirobot is optimized to provide enough dexterity to perform suturing and knot-tying tasks.

1997 Prototype Telesurgical Workstation

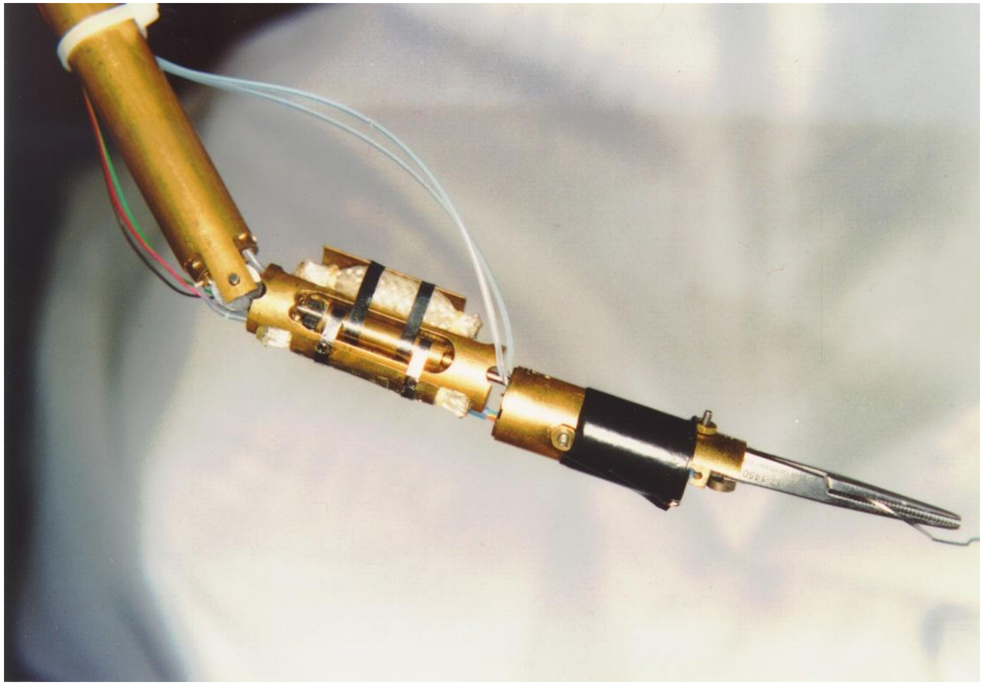
Surgical Master

Positioning Robot



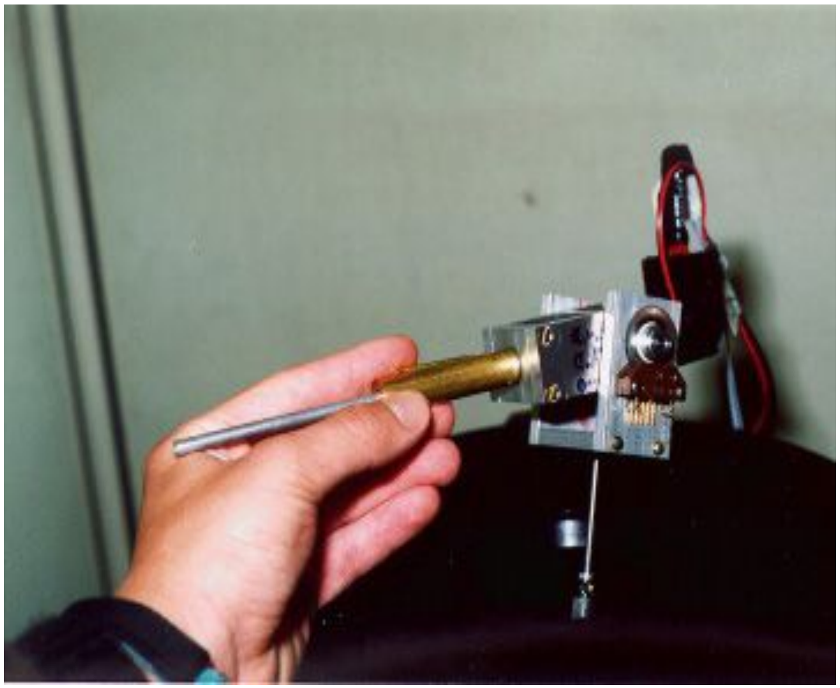
Laparoscopic Manipulator

Next Generation End-Effector



- Streamlined -- No Snagging at Canula
- Shorter -- Better Access in Small Spaces

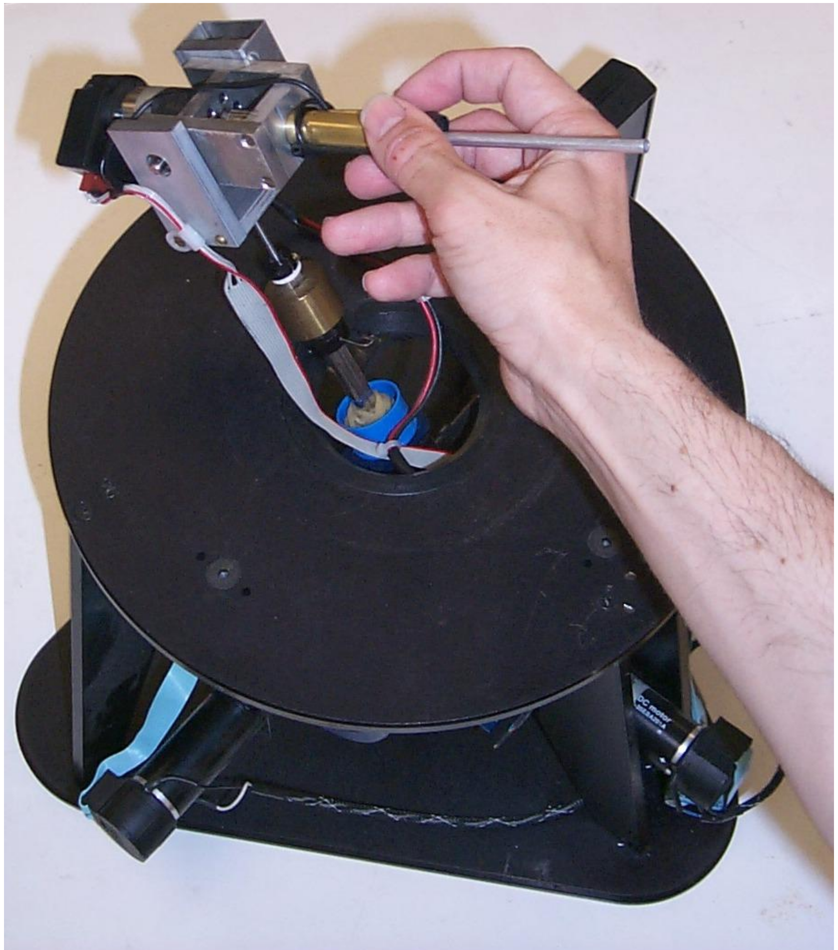
Haptic Human Interfaces

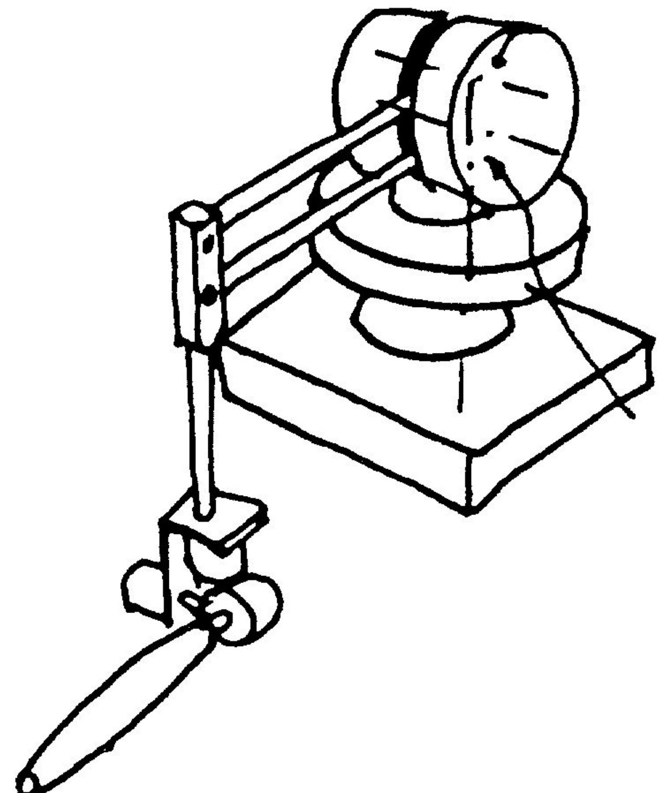


Surgical master stylus will include a finger masters with a stereo tactile display unit.

- The human interface is crucial to telesurgical workstation performance
- The surgeon is provided with an intuitive interface to control the manipulator
- The surgeon receives feedback, restoring the dexterity and sensation of open surgery

Next Generation Joystick





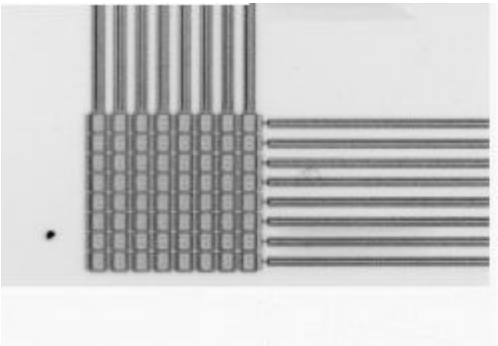
- Imperceptible Stiction
- Wide Range Of Motion

Tactile Sensing

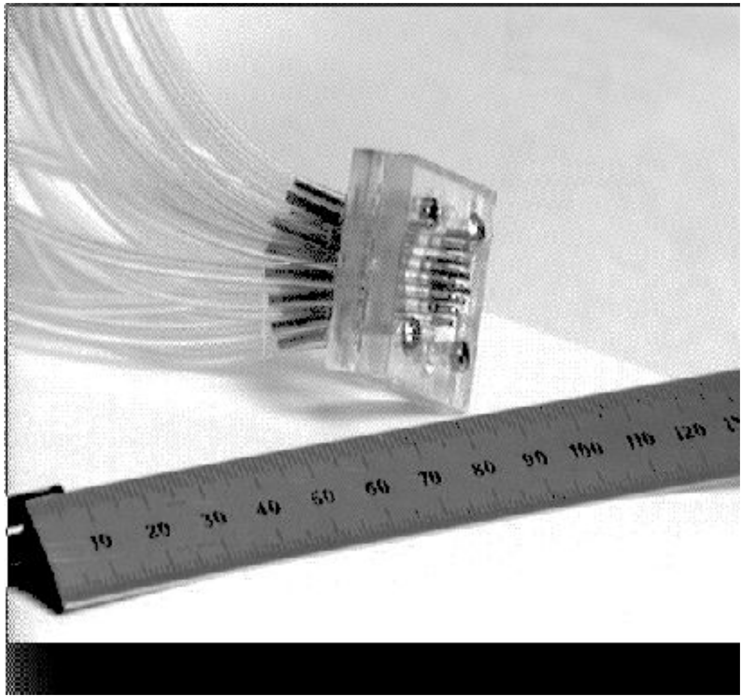
- Tactile sensation allows the surgeon to feel structures embedded in tissue
- Teletaction allows sensing and display of tactile information to the surgeon
- A tactile sensor array can be used to sense contact properties remotely
- To provide local shape information, an array of force generators can create a pressure distribution on a fingertip, synthesizing an approximation to a true contact

Tactile Sensor Array

- The small tactile sensor is designed to be mounted on a laparoscopic manipulator—each sensor consists of an 8´8 array of capacitive sensor cells covered by a rubber layer that serves as a low-pass spatial filter
- When pressure is applied to the array, the resulting deformation causes changes in capacitance of the affected cells—thus contact can be detected and localized, and a profile of contact forces surmised

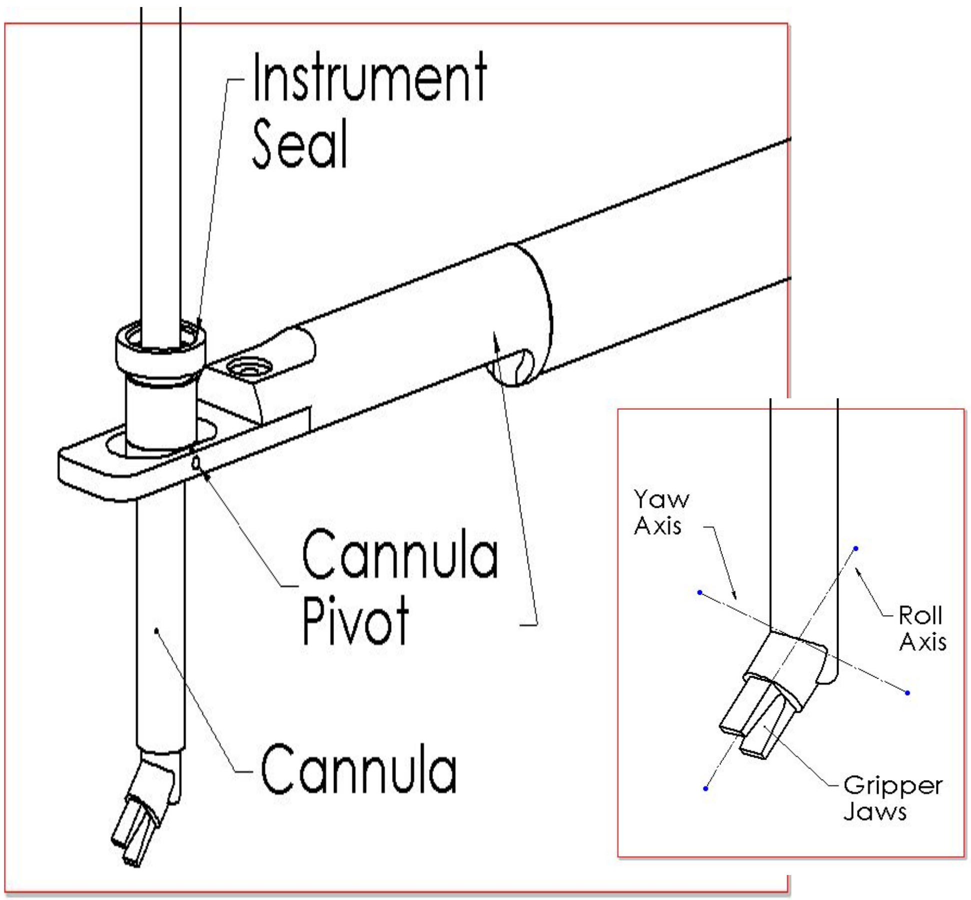


Tactile Display System

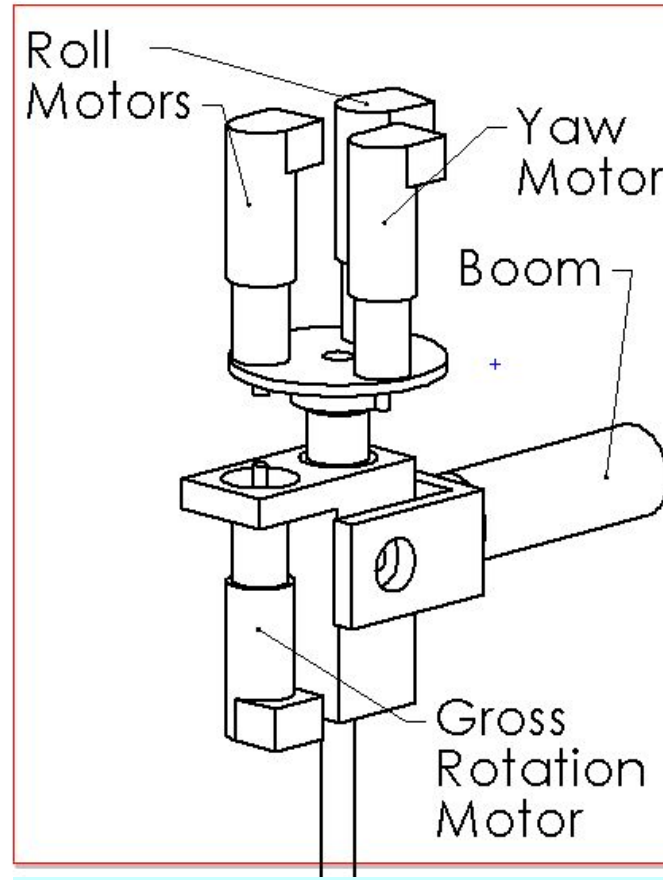


- Prototype 5´5 pneumatic display has a maximum force range of 0.3 N per element, a 3 dB point of 8 Hz, and 3 bits of force resolution
- Design parameters need to be determined through psychophysical experiments
- Tests with a bidigital mock tactile display will be used to help determine how well people can feel features embedded inside soft media

Fine Motion Manipulator

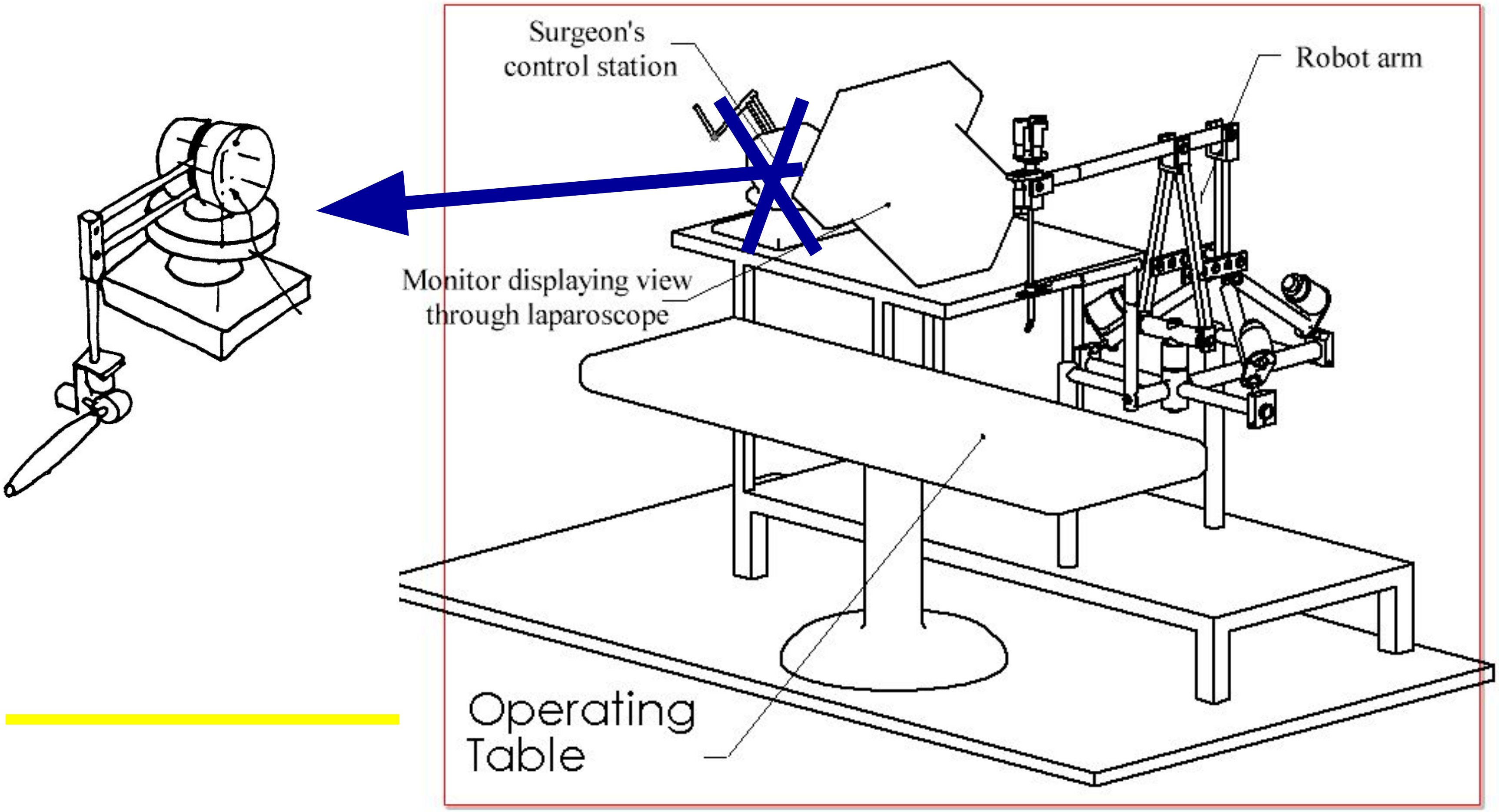


The cannula incorporates a seal which prevents CO2 from escaping from the patient. The pneumatically actuated gripper is rotated about the roll and yaw axes by the roll and yaw motors.

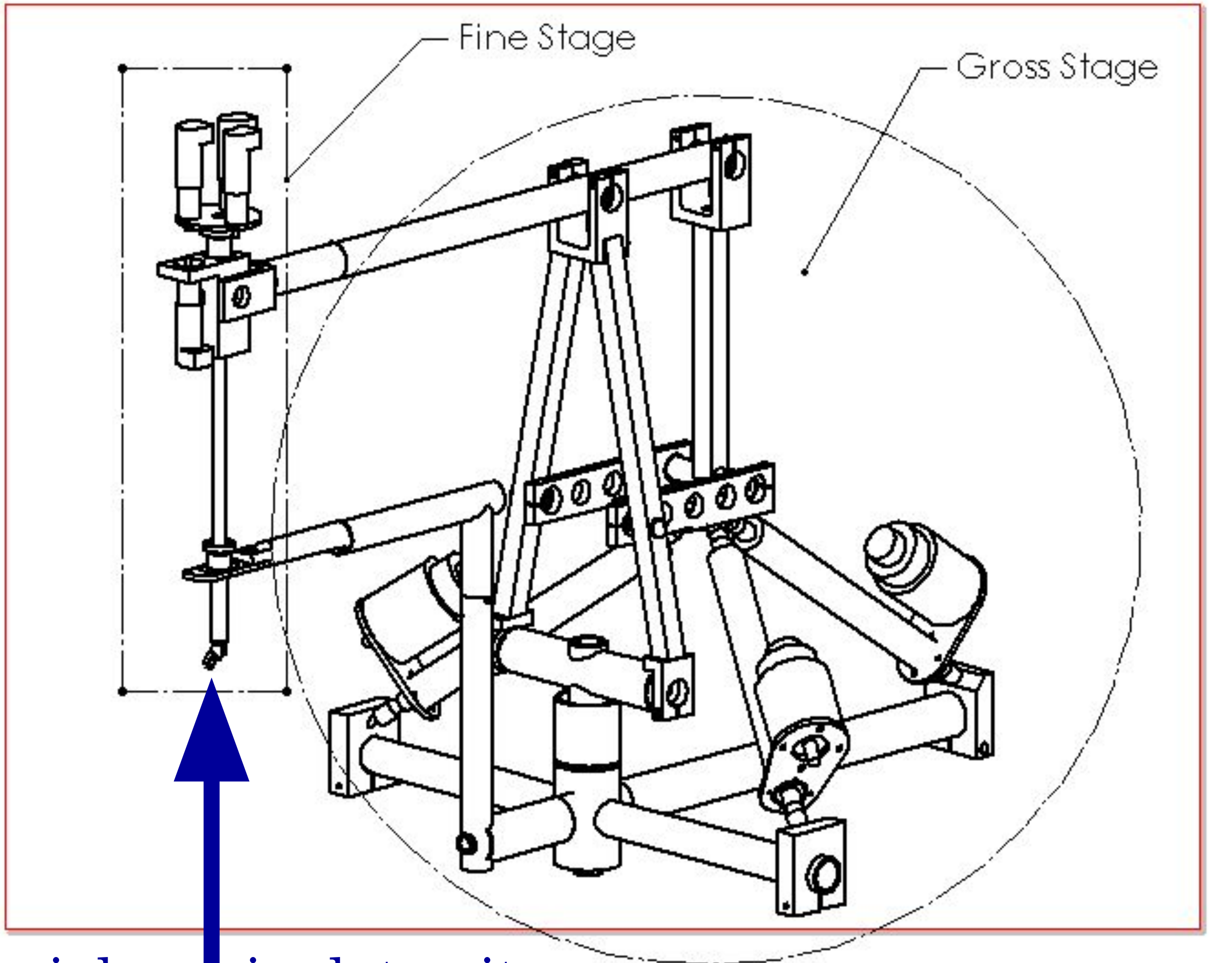


The roll and yaw motors rotate with the instrument shaft when the gross rotation motor is actuated.

Control Stick moved to separate cart to eliminate Mechanical Feedback

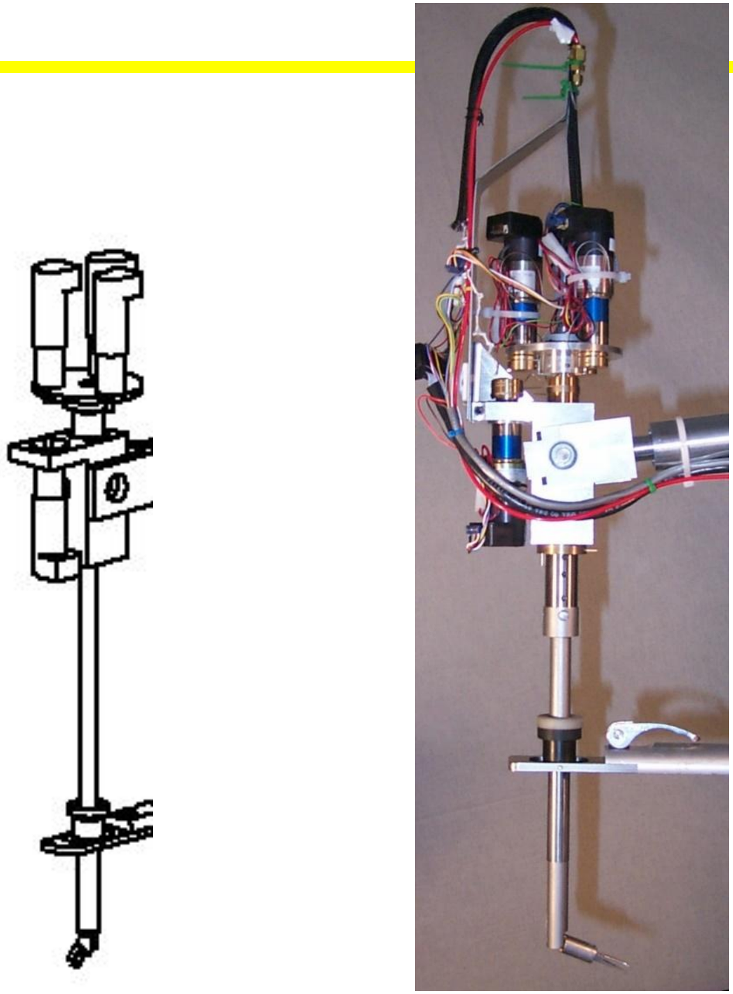


Grappling with a Singularity

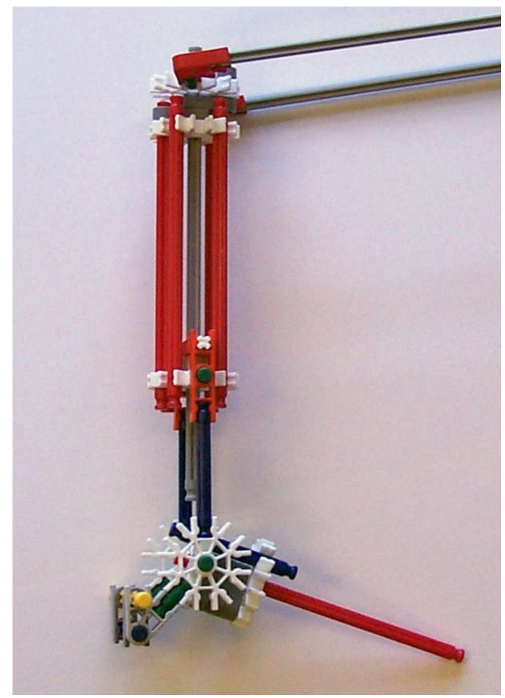


Being a serial manipulator, it has a singularity when the last and third-to-last axes line up.

The *Feel* of the Singularity



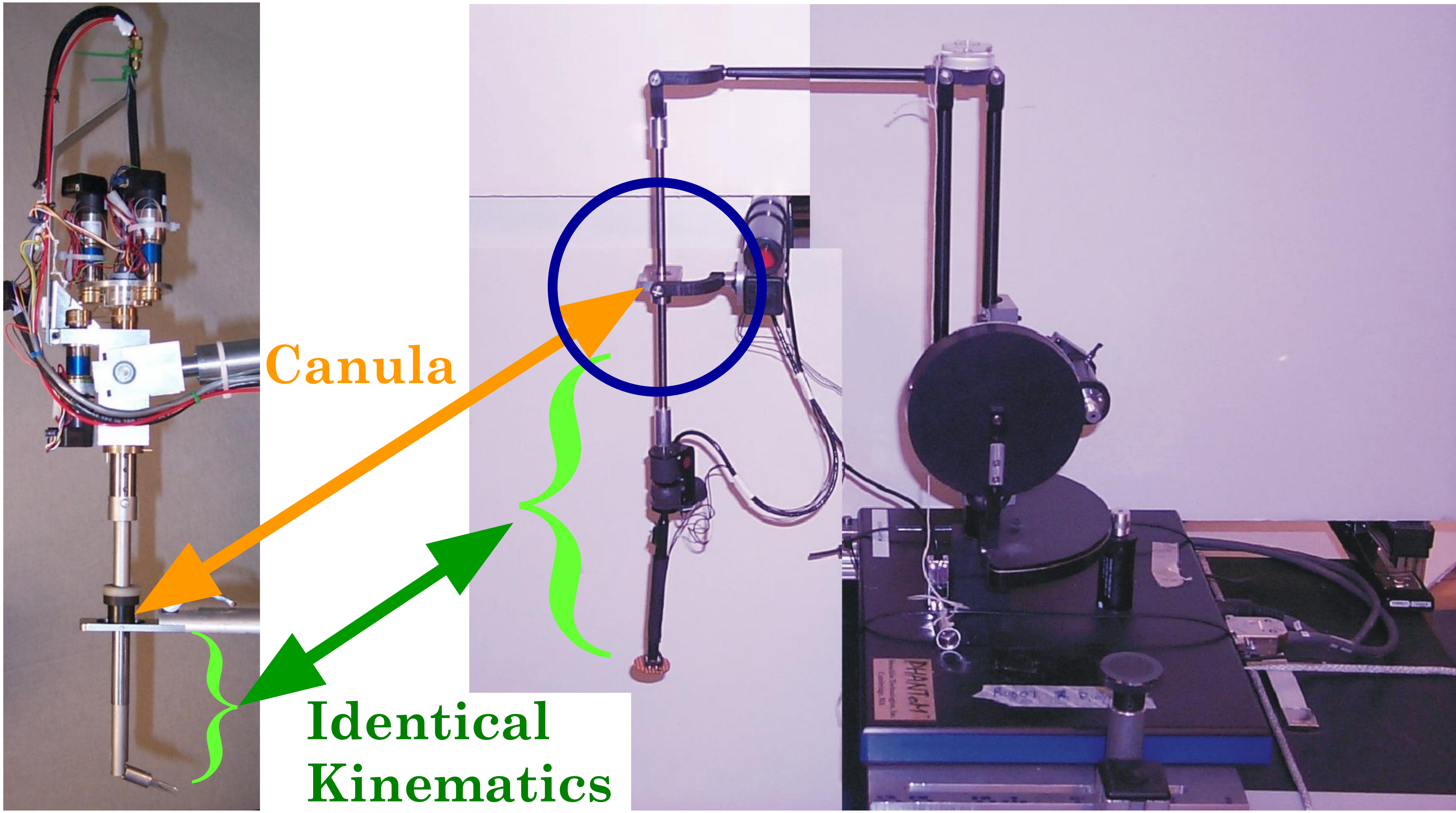
Robot Arm



Toy Model having ***Same Singularity***

Matched Robot Arm Kinematics

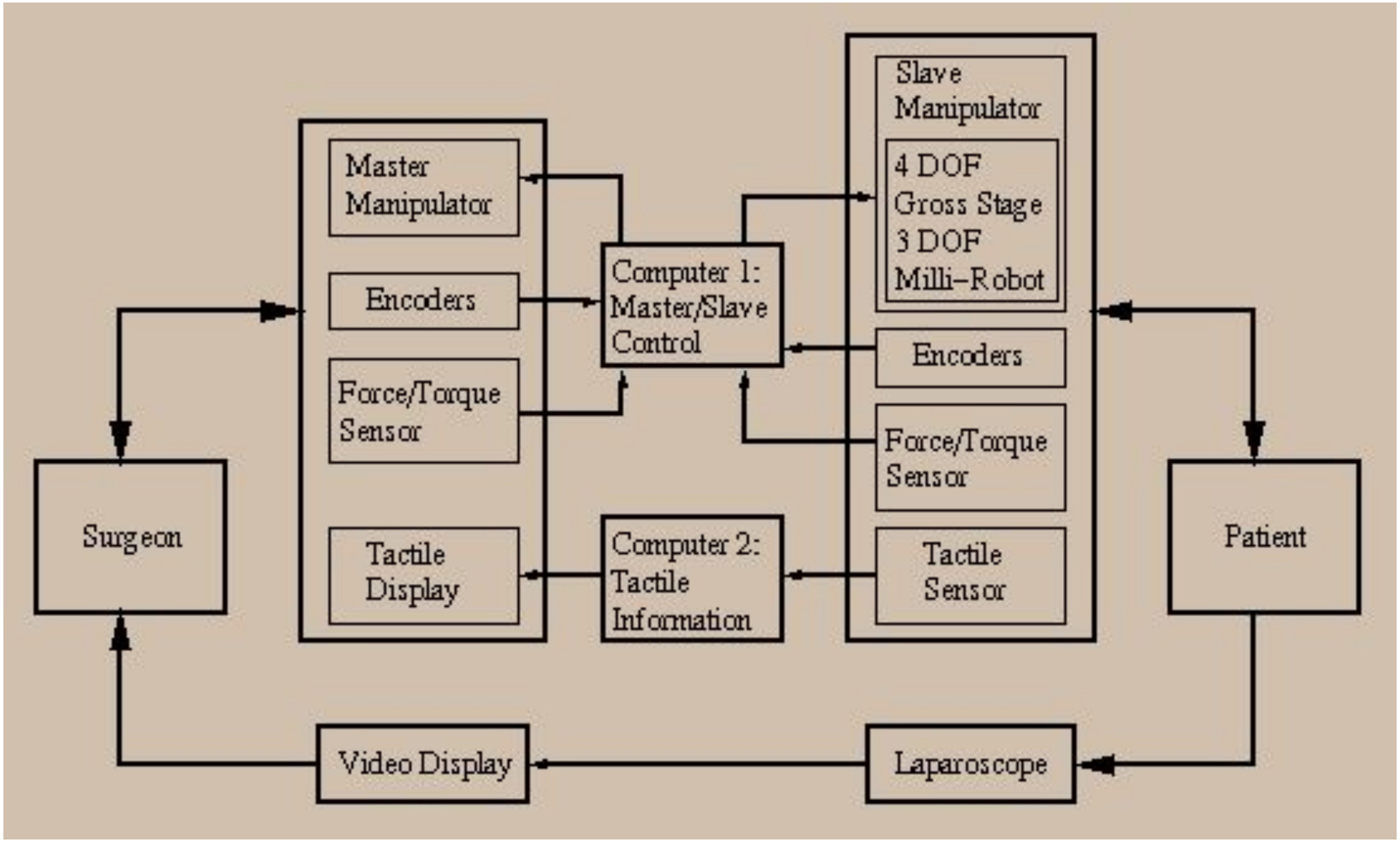
Singularity no longer presents a problem!



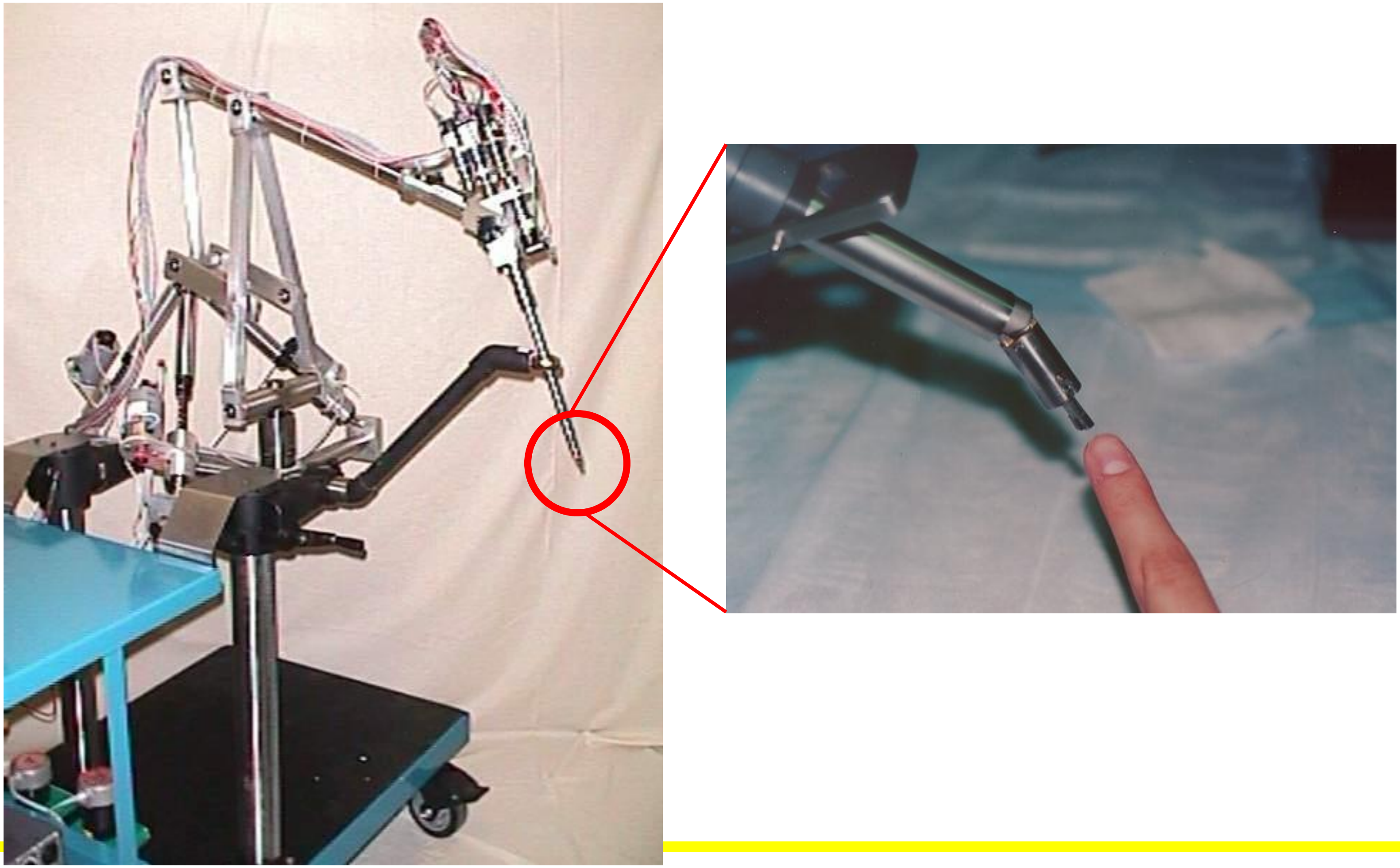
Robot Arm

Control Stick

Bilateral Teleoperation System Design



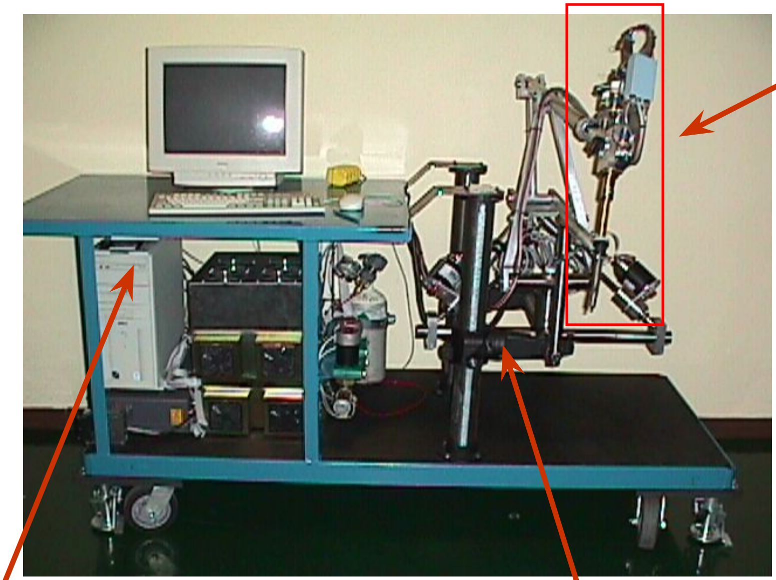
UCB/UCSF Laparoscopic Telesurgical Workstation

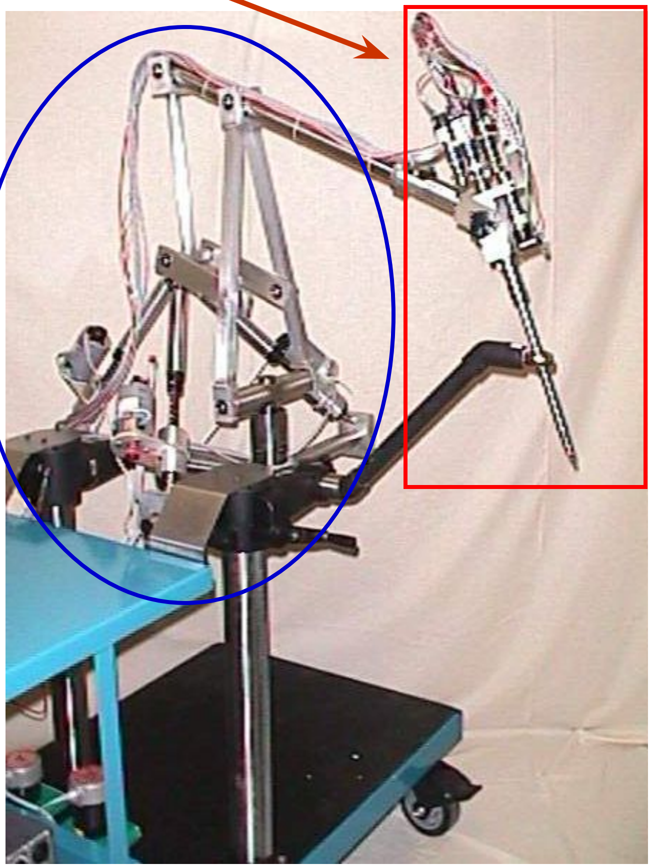


1998 Prototype Telesurgical Workstation

1998 Prototype Workstation

Fine Motion Stage





Manipulator Control Computer

Gross Positioning Stage

ROBOTIC MANIPULATOR

Telesurgical Workstation

Gross Positioning Stage

Cannula

Manipulator Control Computer

Millirobotic Manipulator

Telesurgical Workstation

OPERATING PROCEDURE

A description of how to control the robot in surgical procedures has been developed for training surgeons

ANIMAL TRIALS

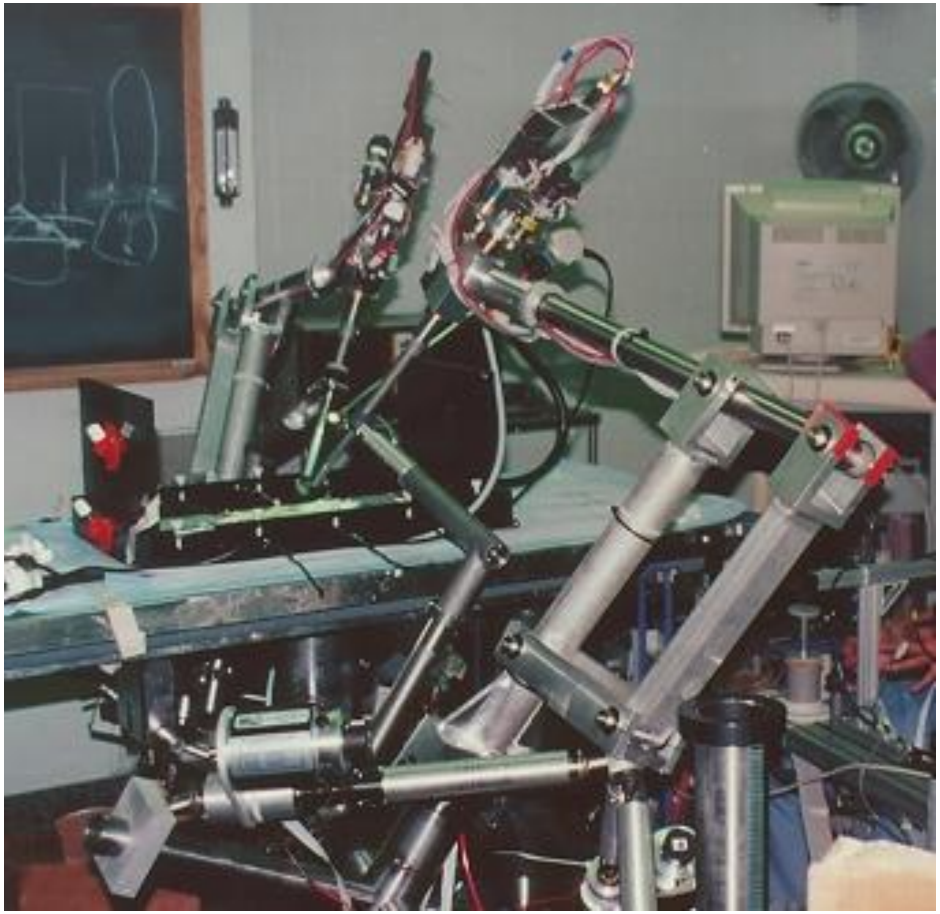
Department of Experimental Surgery, University of California, San Francisco (8/4/98)

Surgeons operated the robot, developing skills moving the robotic arm, grabbing and releasing needles, followed by suturing into the stomach (a tough muscular organ) of an anesthetized pig.

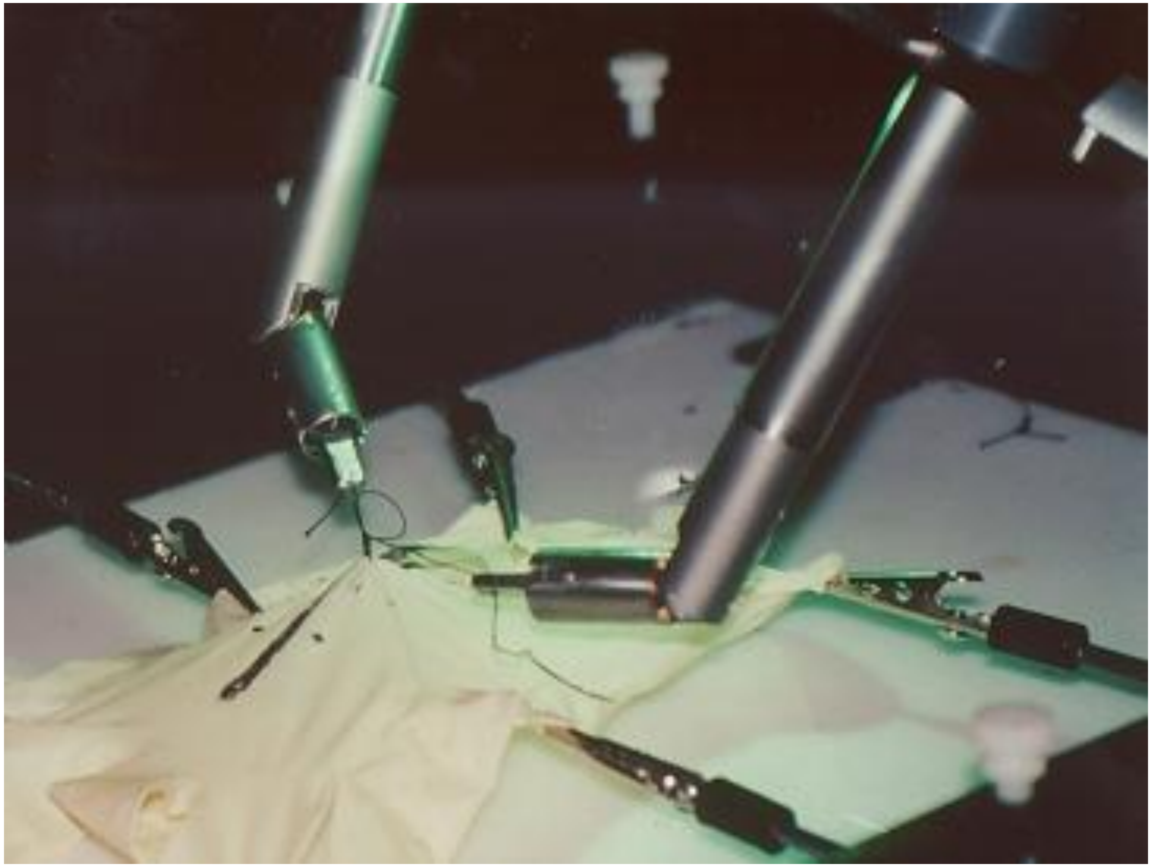
Surgeons also tied knots with the assistance of a conventional laparoscopic tool held by another surgeon.

- Bimanual system delivered to UCSF Nov. 1999

UCB/UCSF Bimanual Laparoscopic Telesurgical Workstation



UCB/UCSF Laparoscopic Telesurgical Workstation



UCB/UCSF Laparoscopic Telesurgical Workstation

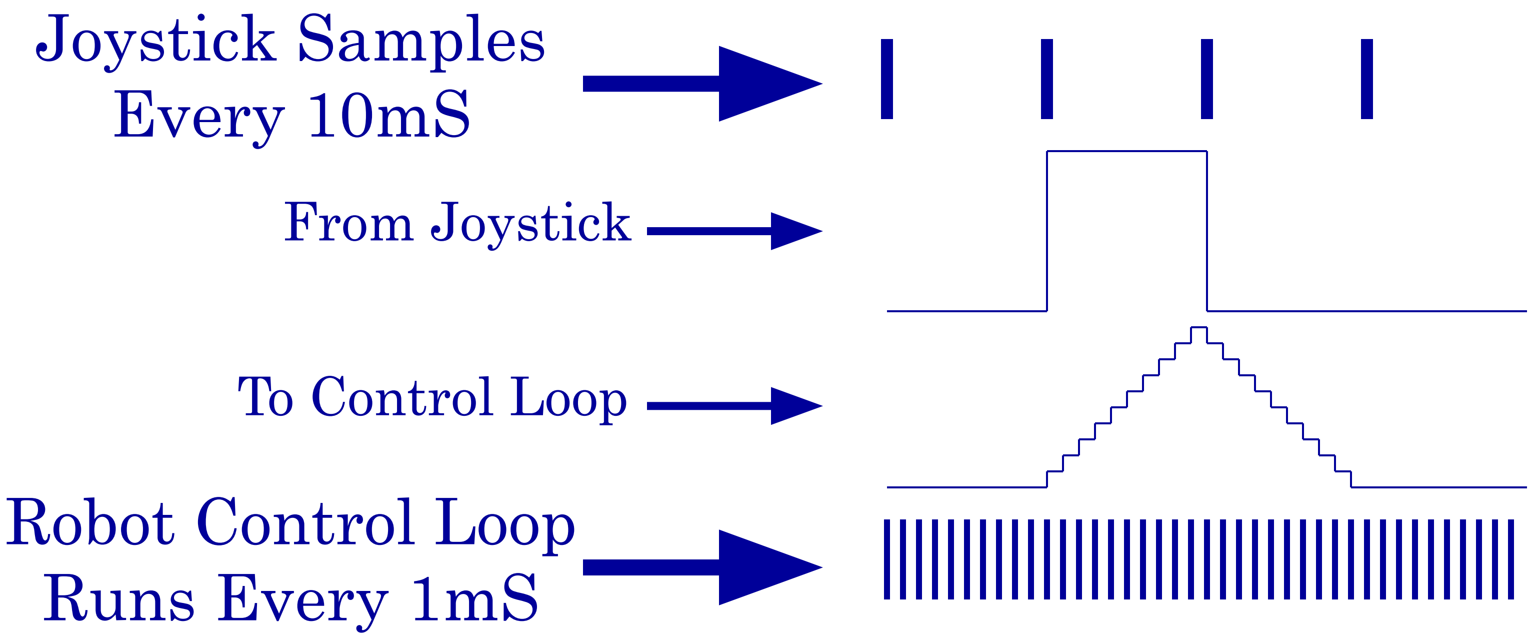
UCB/UCSF Laparoscopic Telesurgical Workstation

- **Experimental results**
  - *Ex vivo* suturing
  - *In vivo* suturing
  - ongoing — Performance comparison/evaluation
  - approved — Complete procedure

ANIMAL LAB TRIALS 1998

Suturing with Unimanual System, 1998

Jumpy Joystick?



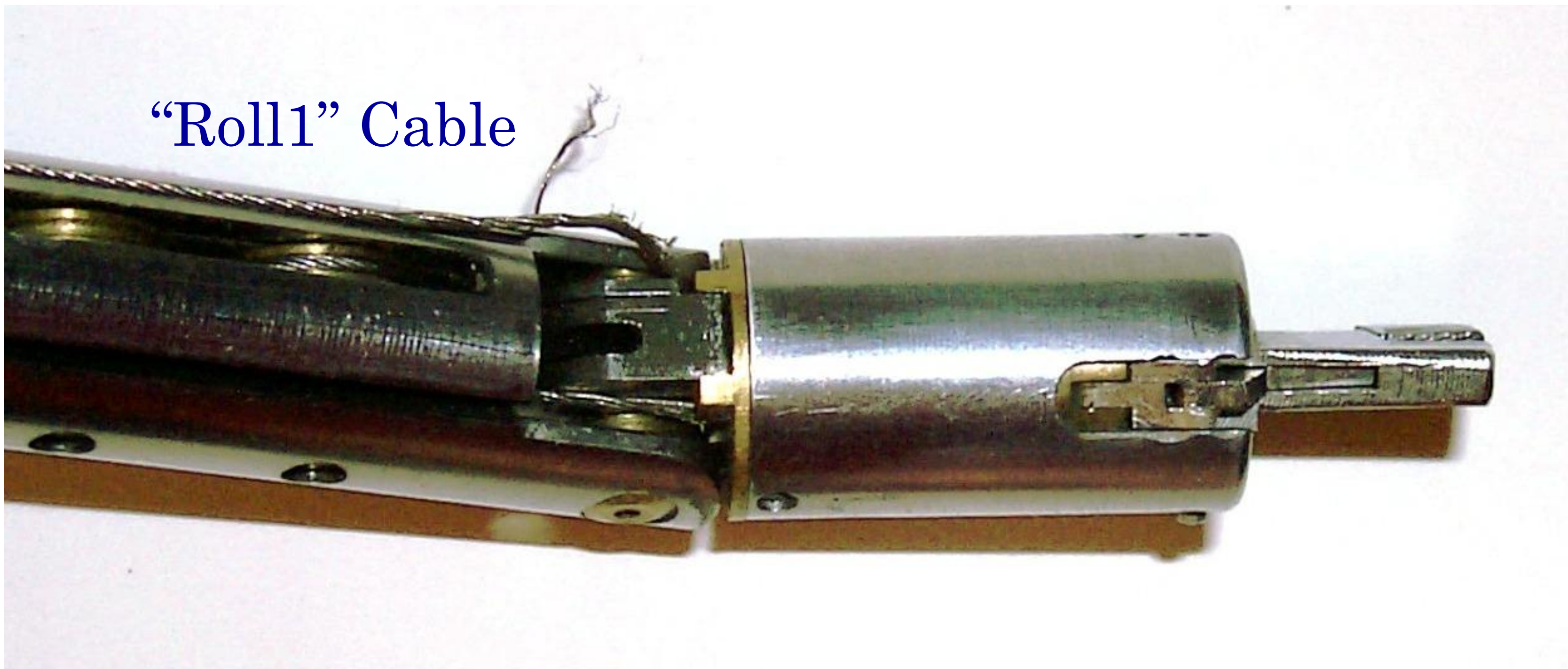
Each jump for new Joystick data has been ***reduced 10-fold***
This resulted in very noticeably smoother and quieter operation

Curved Jaws

Thread was hard to wrap onto this jaw, then got stuck on it! *Difficult to tie knots.*

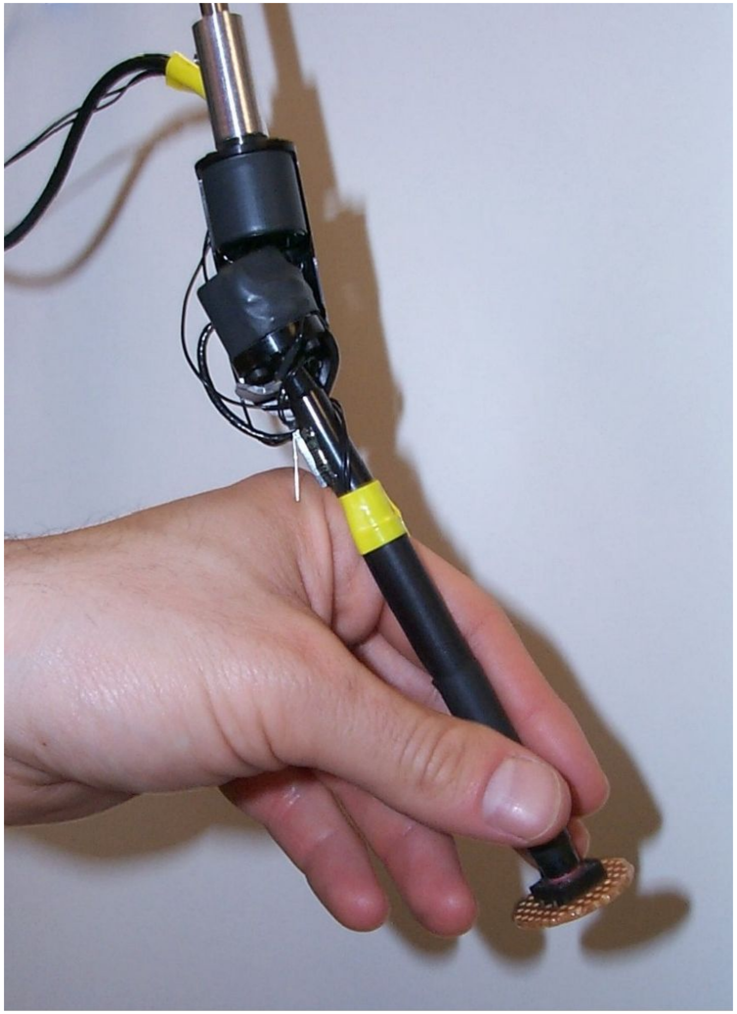
More room to wrap, thread glides off. *Easy to tie knots!*

Frayed Steel Tendon Cable

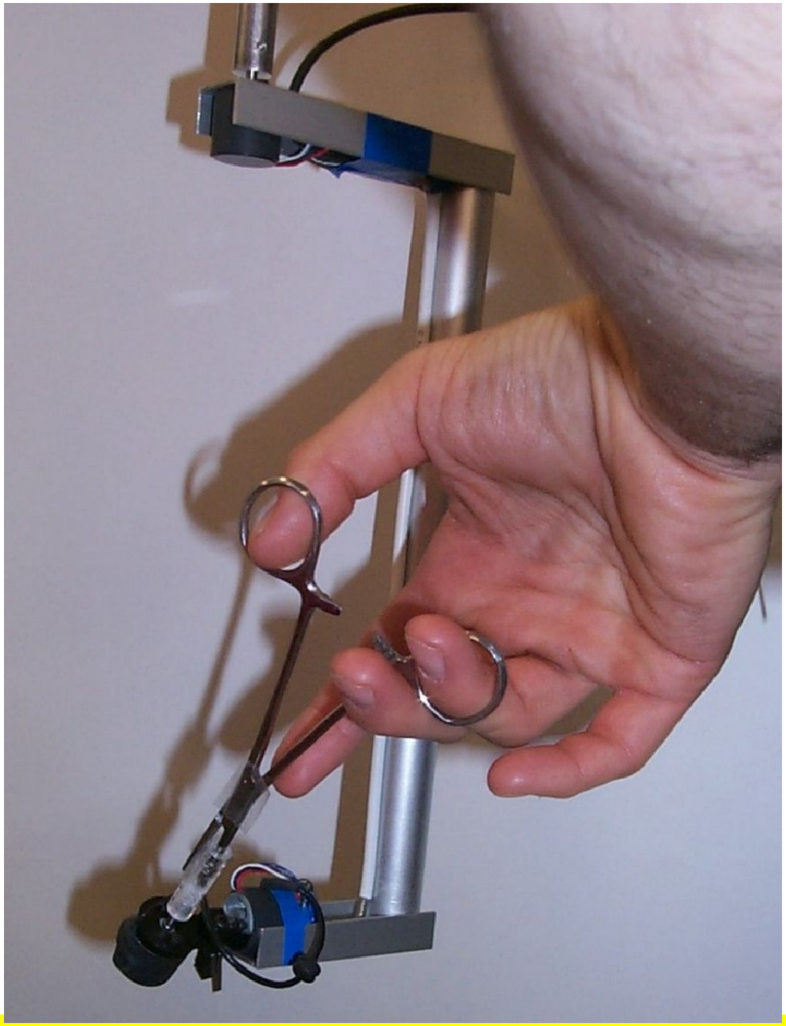


End Effector of the Unimanual Robot

Experimental Control Handle



Existing



Experimental

Laparoscopic Telesurgical Workstation – What is Next ?

- User interface / master workstation
  - Immersive visual display
  - Camera motion
- New manipulator designs for smaller scale
  - Cardiac surgery
  - Fetal, neonatal and pediatric surgery
- High fidelity teleoperation controller

Teleoperation Algorithms Optimized for Surgical Manipulation

- Task based performance goals rather than an "ideal" teleoperator response
- Oriented towards improving performance with respect to human perceptual capabilities

For this it is necessary to

- Experimentally quantify human perceptual capabilities, and
- Develop control design methodologies which can incorporate these new performance measures

Bilateral Controller Design for High Fidelity Teleoperation

- Psychometric parameters of the operator
- Fidelity measure
- Control design
- Experimental evaluation
- Compare sensory schemes

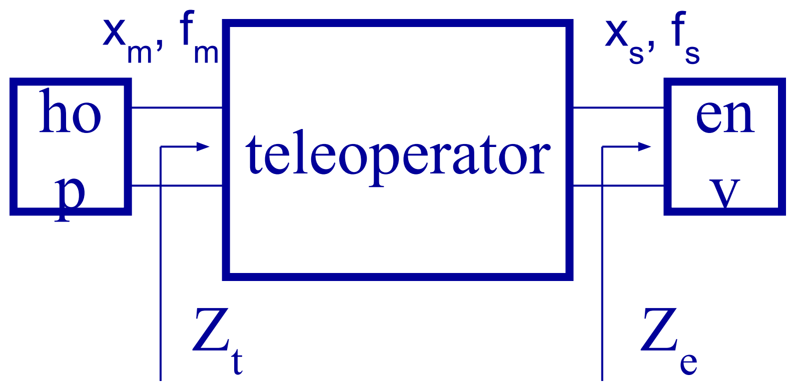
What is Our Contribution ?

- Manipulation of deformable objects has not been studied in the literature
- Control design is explicitly oriented towards optimizing the task based performance objective
- Robust control methodology has been applied to handle environment and operator uncertainties

Fidelity in Teleoperation

- Ideal tracking (Hannaford)

$$x_m = x_s \quad , \quad f_m = f_s$$



- Transparency (Lawrence)

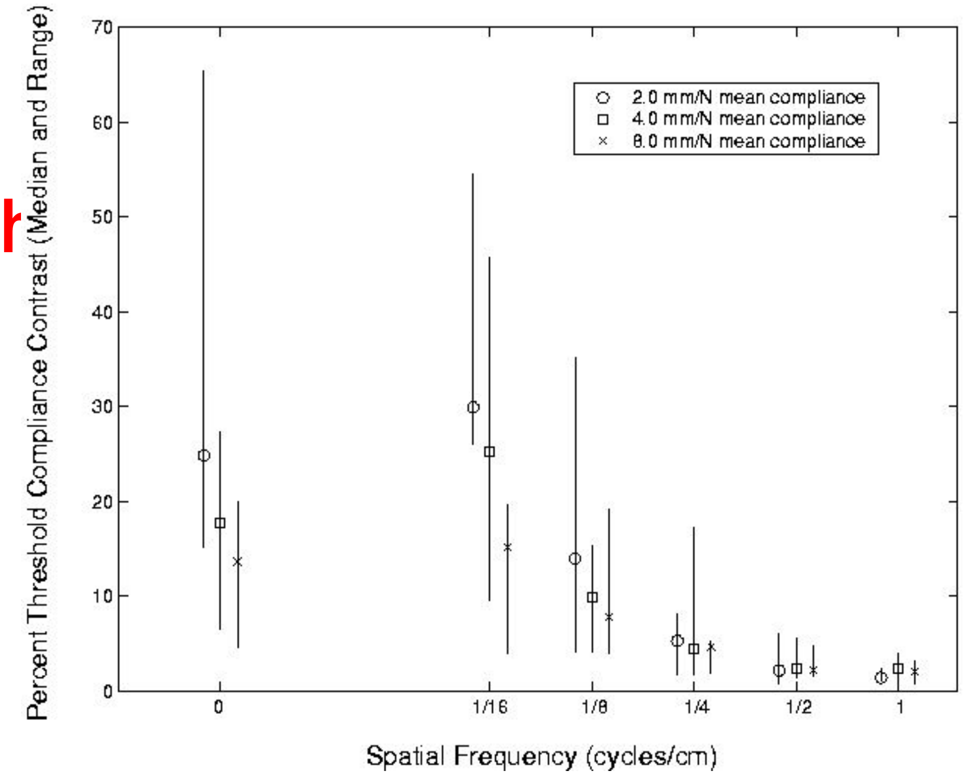
$$Z_t = Z_e$$

- Sensitivity to environment impedance changes (Cavusoglu)

$$\text{maximize} \quad \left\| W\left(\frac{dZ_t}{dZ_e}\right) \right\|_\infty$$

Psychometric Parameters of the Operator

- Sensitivity of the human operator to stiffness and force stimuli increases with frequency



Robust Stability

Loop gain of the teleoperator is given by

$$P = -h_{12}h_{21}\frac{1}{\left(h_{11}+Z_{hop}\right)}\frac{Z_e}{\left(1+h_{22}Z_e\right)}$$

Given the uncertainties

$$Z_e \in \hat{Z}_e \;,\; Z_{hop} \in \hat{Z}_{hop}$$

It is possible to find W_{ue} , W_{uh} such that

$$\left|\frac{1}{h_{22}\tilde{Z}_e}\frac{Z_e-\tilde{Z}_e}{1/h_{22}+Z_e}\right| < \left|W_{ue}\right| \;,\; \left|\frac{\tilde{Z}_{hop}-Z_{hop}}{h_{11}+Z_{hop}}\right| < \left|W_{uh}\right| \;,\; W_u = W_{ue}+W_{uh}+W_{ue}W_{uh}$$

Then, the closed loop system is stable for all plants iff:

1. It is stable for the nominal case
2. $\left\|W_u T\right\|_\infty \leq 1 \;,\quad T = P/(1+P)$

Tracking Requirement

- Using transparency as fidelity leads to a trivial solution:

  Surgical manipulator doesn't move, and master manipulator simulates the environment stiffness !…

- Tracking constraint on the disturbance sensitivity of the forward position loop to avoid trivial solution :

$$\left\| W_p S \right\|_\infty \le 1 \quad , \quad W_p(j\omega) = 1/b(j\omega)$$

Tracking error less than $|b(j\omega)|$ for a unit magnitude sinusoidal input.

Controller Design as a Task Based Optimization

Control design problem is formulated as an optimization:

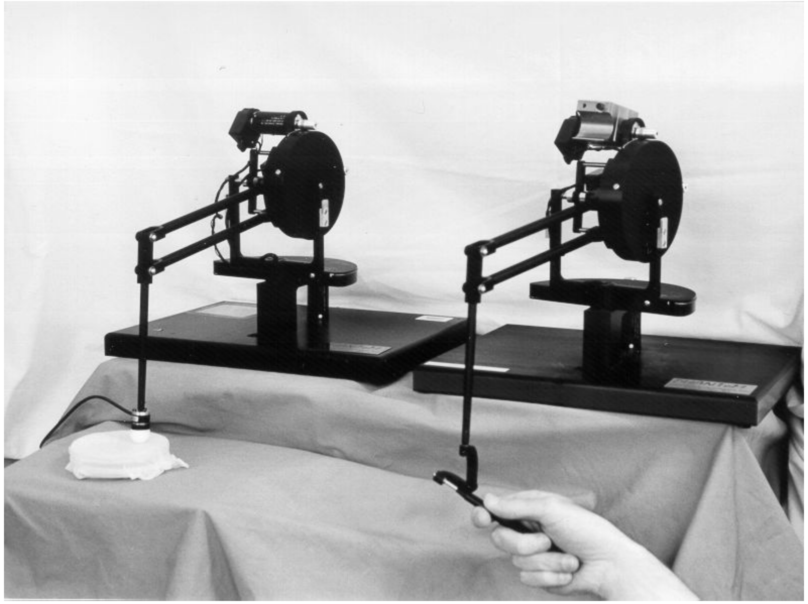
$$\arg \sup_{\substack{\|W_u T\| \le 1 \\ \text{nom. stable} \\ \|W_p S\| \le 1}} \left\| W_s \frac{dZ_t}{dZ_e} \right\|_\infty$$

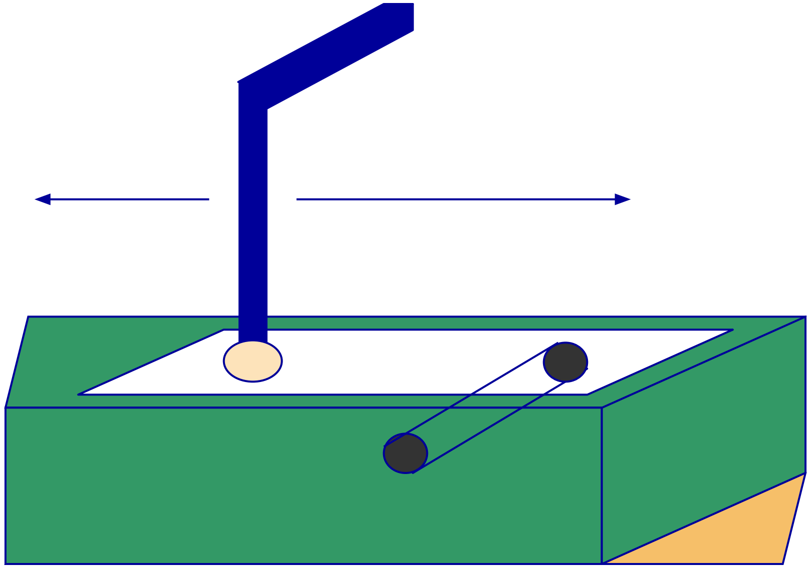
Optimize the fidelity for controllers which

- **Satisfy robust stability for specified operator and environment uncertainties**
- **Satisfy free space tracking requirement**

Formulation also enables comparison of sensory schemes

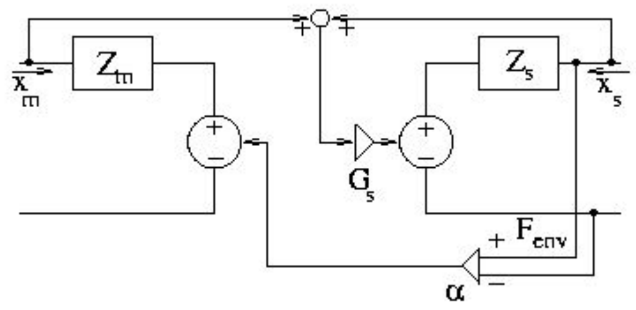
Experimental Evaluation



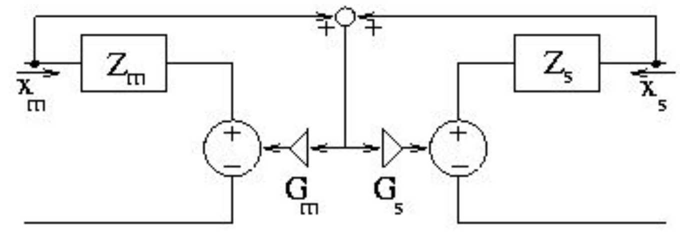


Experimental Evaluation

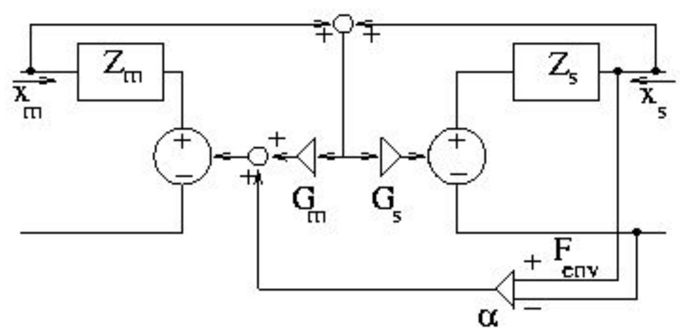
Kinesthetic Force Feedback



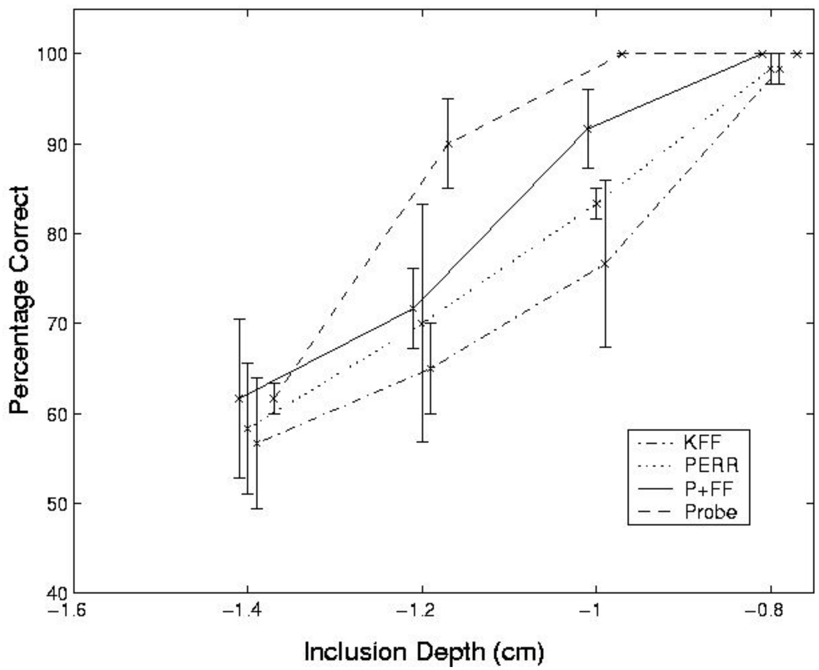
Position Error Based FF



Position + Kinesthetic FF



Experimental Evaluation - Results



- P+FF>PERR>KFF

  Using a force sensor improves the impedance discrimination ability
- Dynamic properties and the noise of the force sensor is a significant factor and degrades the performance

Teleoperation Controller Design

- Developed a general theoretical and experimental methodology to design and compare teleoperation controllers
- Applicable to future teleoperator designs with novel actuators, sensors and controllers

Next steps:

- Expand the design tools with more emphasis on sensor and modeling uncertainties
- Apply the methodology to study more fundamental questions in the mechanical design of teleoperators

Virtual Environment Based Surgical Training Simulator

Why is Improved Visualization Needed in Surgery?

- **The advancement of medical imaging modalities (CT, MRI, ultrasound, video-endoscopy) has provided more information to the surgeon.**

- **With more information, there is less unwanted damage to surrounding tissue and less risk is necessary.**

- **But in many current procedures, visualization of the information is poor. This leads to increased errors, and has slowed the adoption of image-guided and minimally invasive techniques.**

- **Improved visualization technology would allow the surgeon to directly see the necessary anatomical relationships.**

Visualization Enables Telemedicine

- It is difficult to transport an injured or ill sailor to expert medical care or to bring the expert to the sailor
- Through remote visualization, the remote expert could be provided information to advise in the sailor's care
- Through telesurgery, a remote surgeon could operate or assist in a procedure

Current Surgical Training

- By apprenticeship
- Possible increased risk to the patient
- Stressful learning environment
- Difficult to standardize techniques or training methods
- Assessment of a surgeon's skill is difficult; assessment is need to verify surgeon's competence to perform a novel procedure
- Minimally invasive techniques require new perceptual-motor relationships that are difficult to learn

Current Training Methods in Surgery

•Apprenticeship	Limitations due to risks to patients Difficulty in diffusion of knowledge
•Textbooks	Two Dimensional
•Training mannequins	Not very realistic Limited variation in pathologies
•Animal experiments	Excessive cost Anatomical differences

Training in Virtual Environments

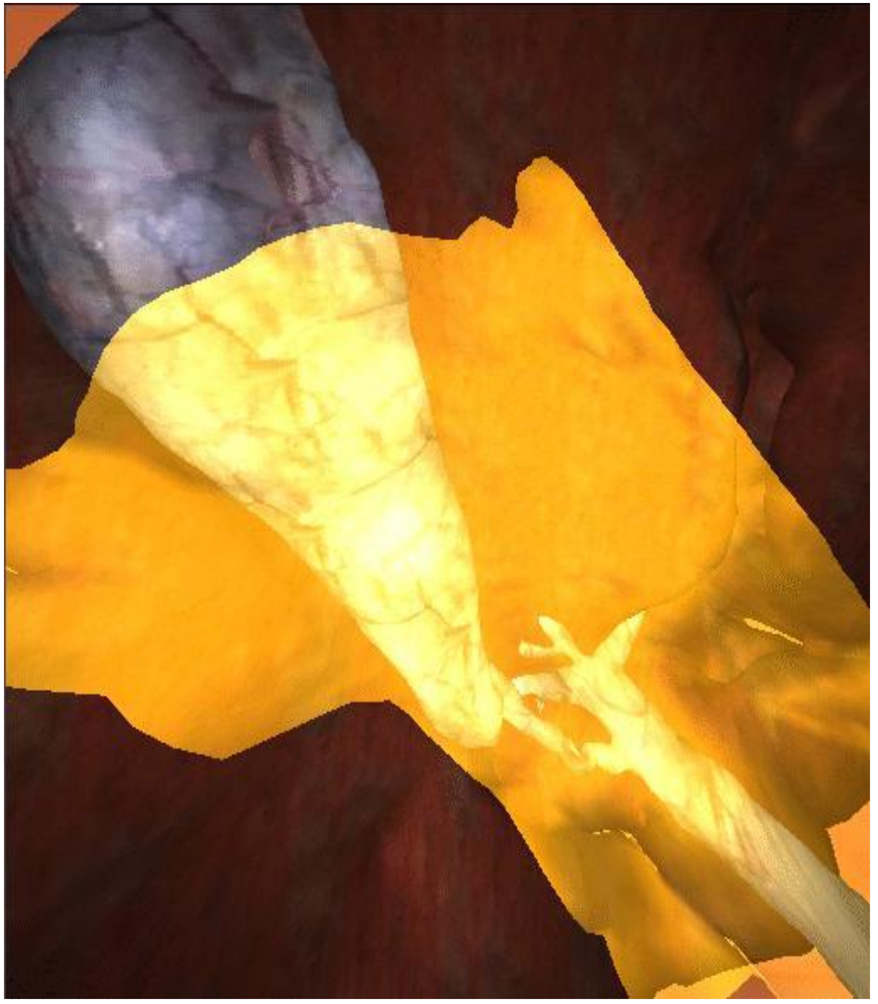
- Unlike textbooks, virtual environments are three dimensional and interactive
- Unlike animal labs, cadavers, or latex models of organs:
  - Can simulate any anatomy or disease state
  - Using computer based training, the presence of an instructor is unnecessary
  - Can automate the assessment of skills and procedural knowledge

Elements of Surgical Simulation

- Geometric models
- Physical models
- Collision detection
- Instrument-tissue interaction (grasping, cutting, stapling, electrocautery)
- Haptic interface
- Visualization

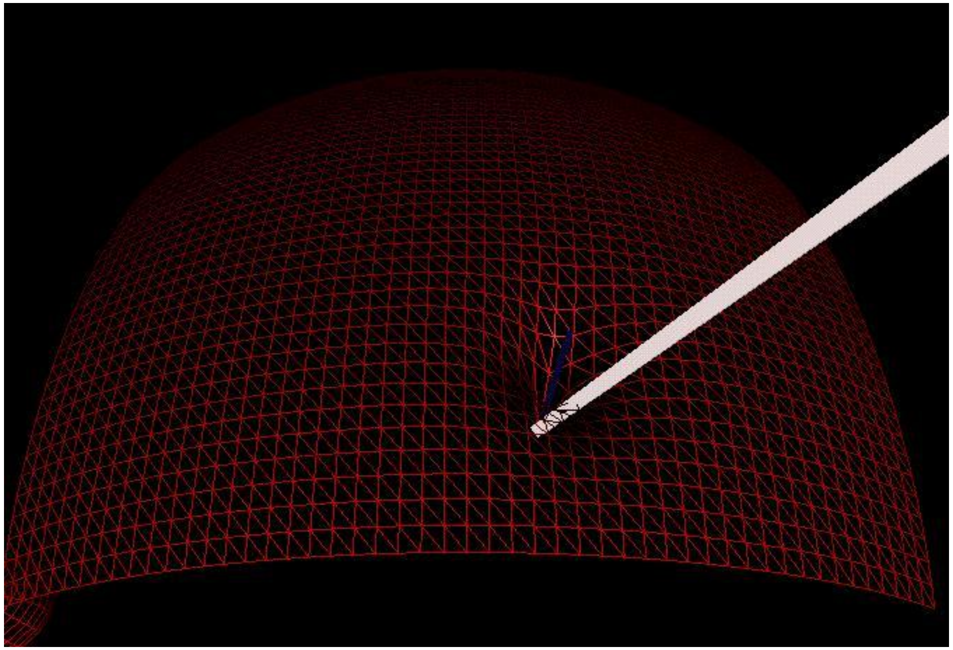
Geometric Modeling

- Simulation accepts any surface mesh
- Current models from commercial hand-segmented Visible Human data
- VCSEL scanner will soon have resolution appropriate for anatomical scale. We will scan animal liver and surrounding organs and incorporate into simulation.



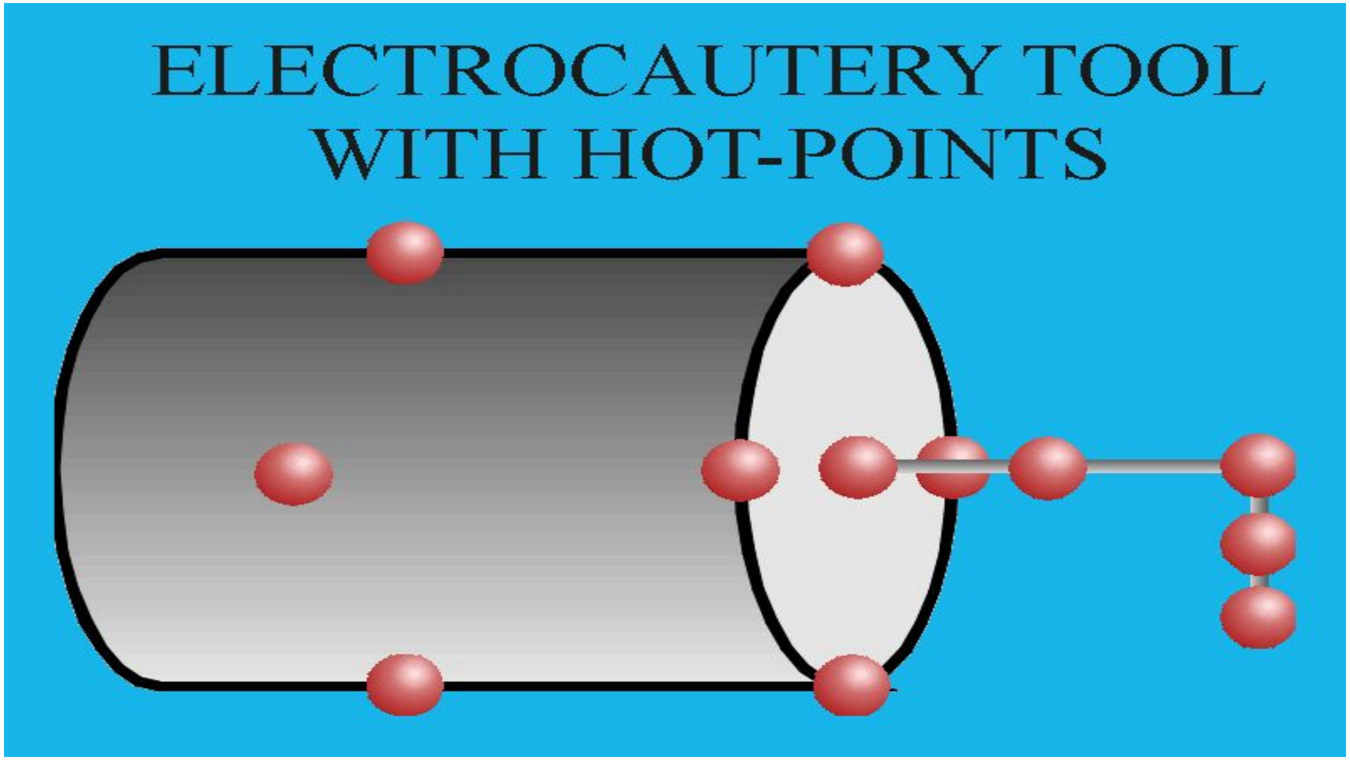
Physical Modeling

- Currently, use simplest modeling methods: surface mesh of masses-springs-dampers, forward Euler integration
- Code uses template structures for easy insertion of new physics functions



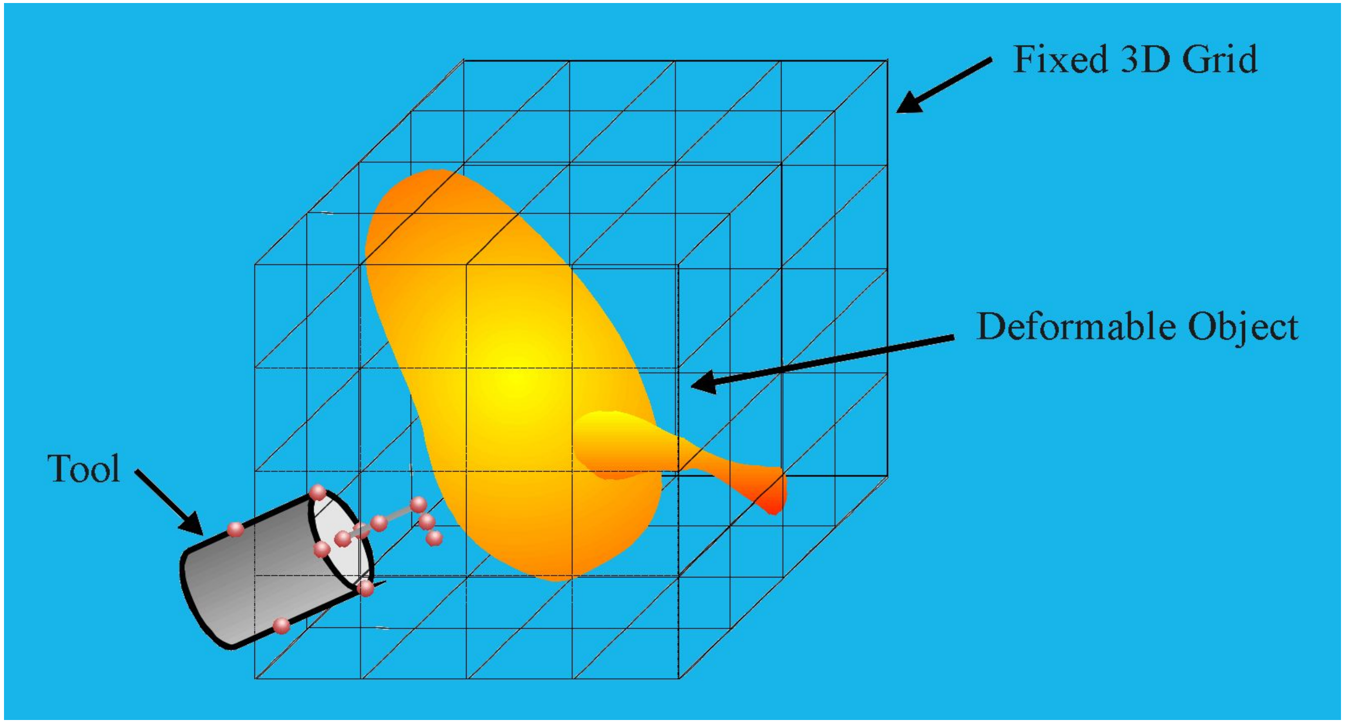
Collision Detection

- **Assign "hot points" at locations on tools that are most significant in tissue interaction**



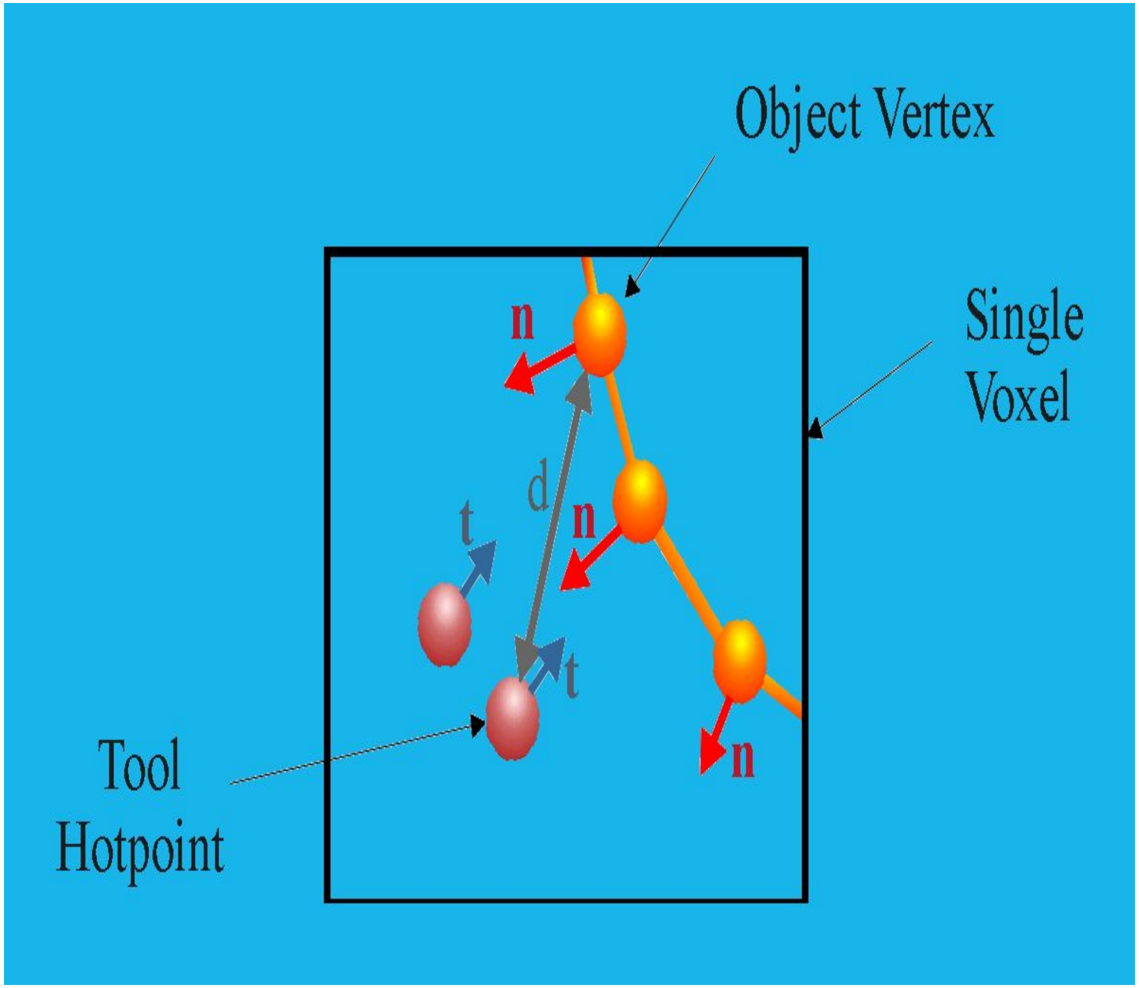
Collision Detection

- **Find voxel of each hot-point (in O(1) time since we have a fixed size grid)**



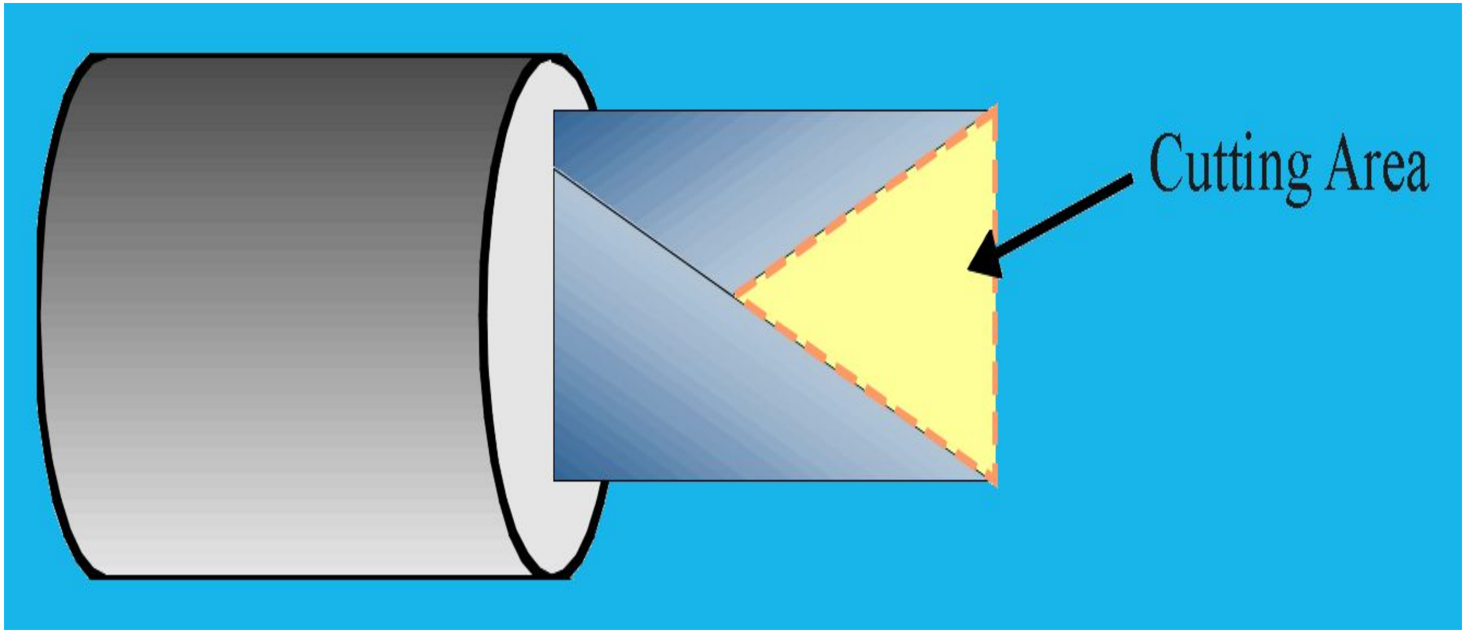
Collision Detection

- **Find vertices in that voxel that are within a distance of R of hot-point (i.e. select vertices where d <= R)**
- **Select those vertices whose normals (n) point against the direction of the tool's motion (t) (i.e. select vertices where n . t <= 0)**
- **Update voxel array as object deforms**



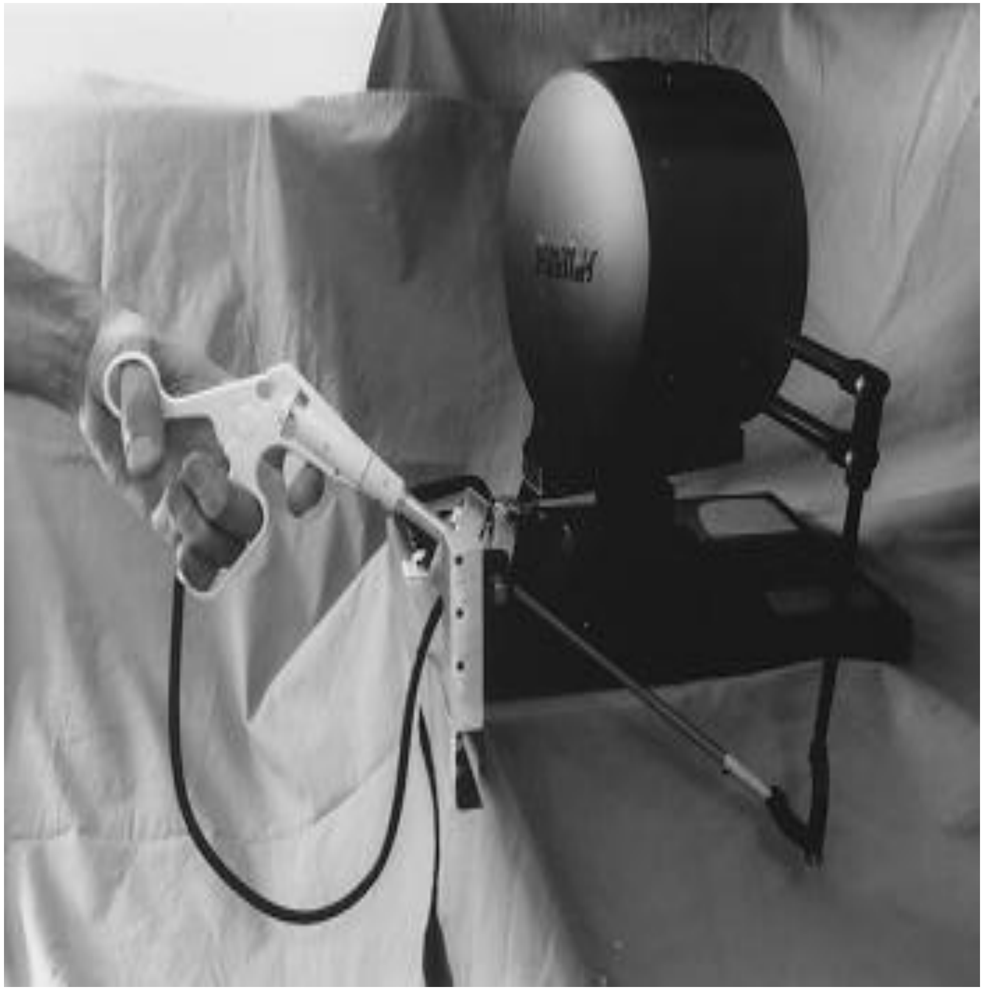
Tissue Cutting

- Calculate the cutting area
- For each face of a given object see if any of its edges intersects the cutting area
- If yes remove the edge and remove the face

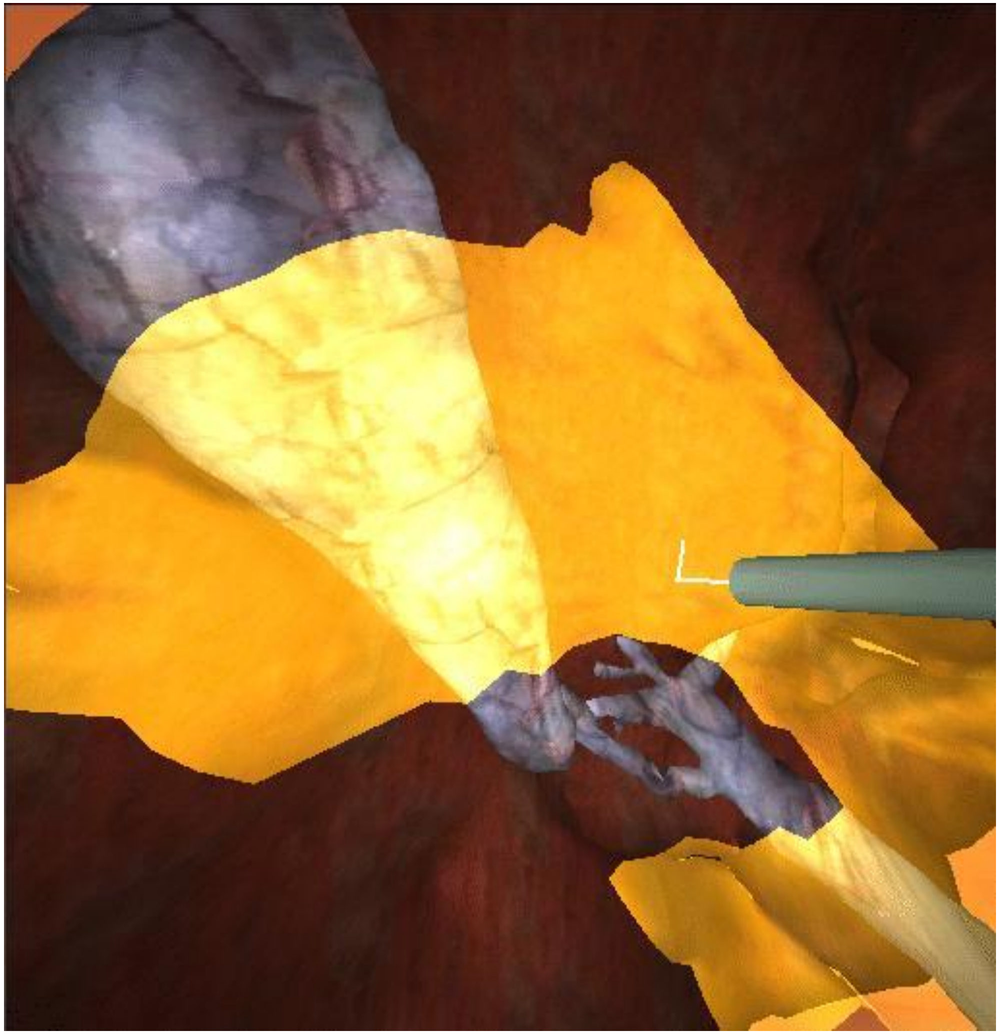


Haptic Interface

- Based on Sensable Tech 3 DOF Phantom
- 4th DOF added with fulcrum and torque about instrument roll
- Duplicate interface for each hand, plus passive device in center to simulate laparoscope



Current Simulation: Gallbladder Removal

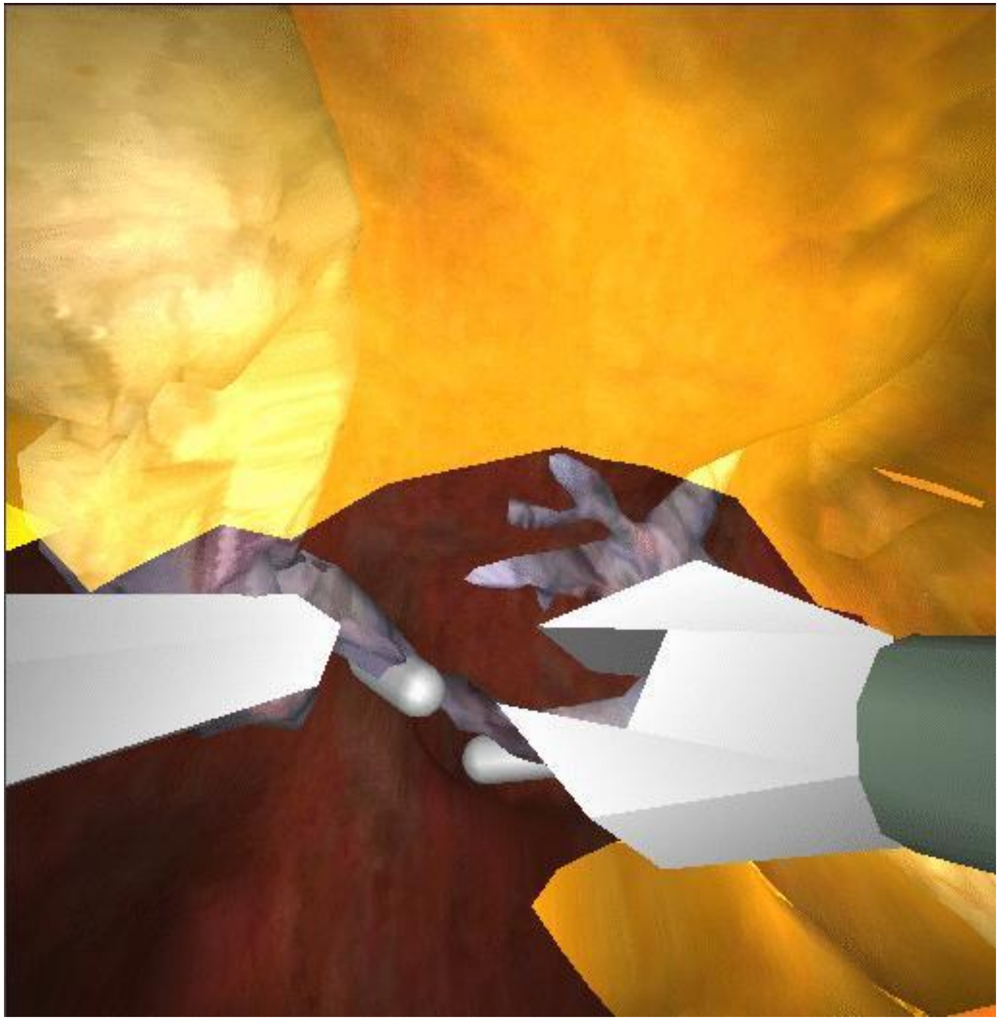


Removal of soft tissue using electrocautery tool

Current Simulation: Gallbladder removal

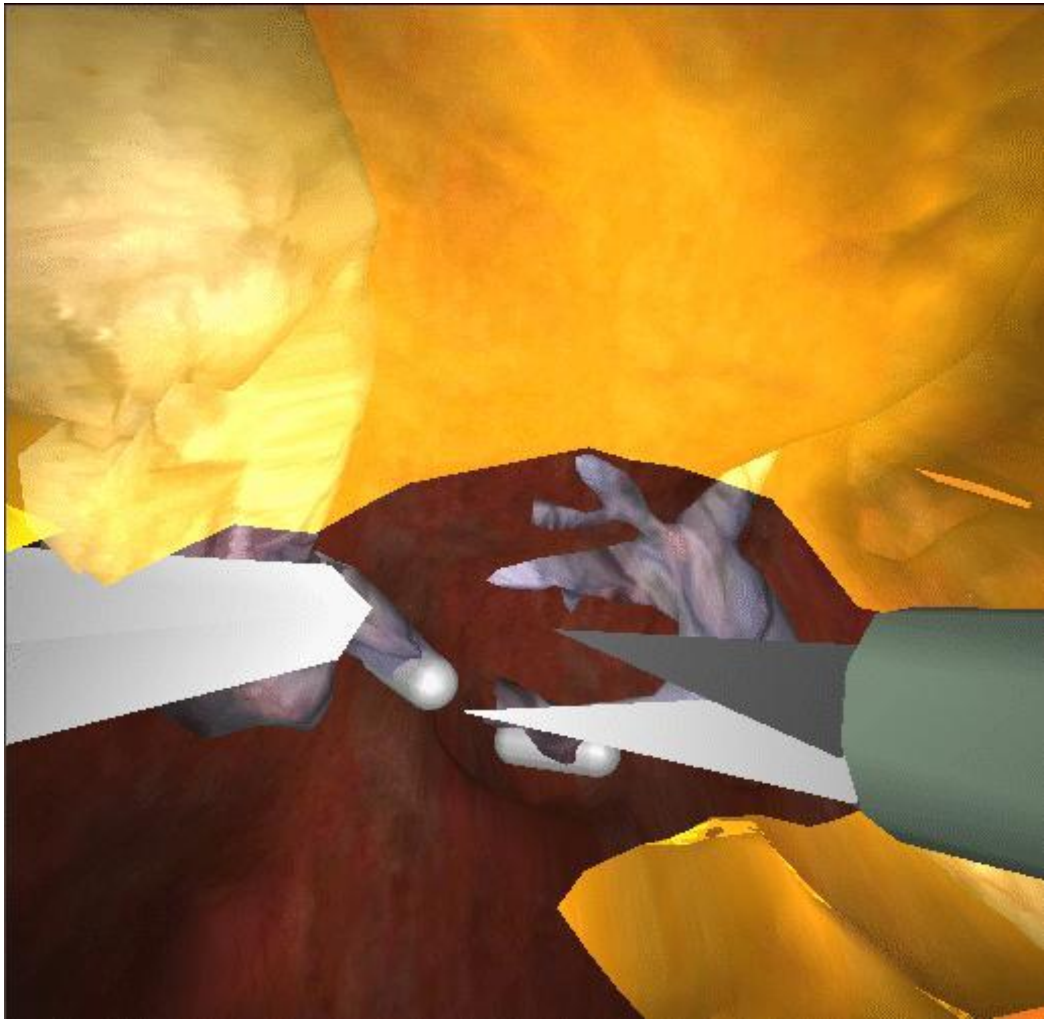
Traction on the gallbladder to stretch cystic duct

Current Simulation: Gallbladder Removal



Staple cystic duct to close it

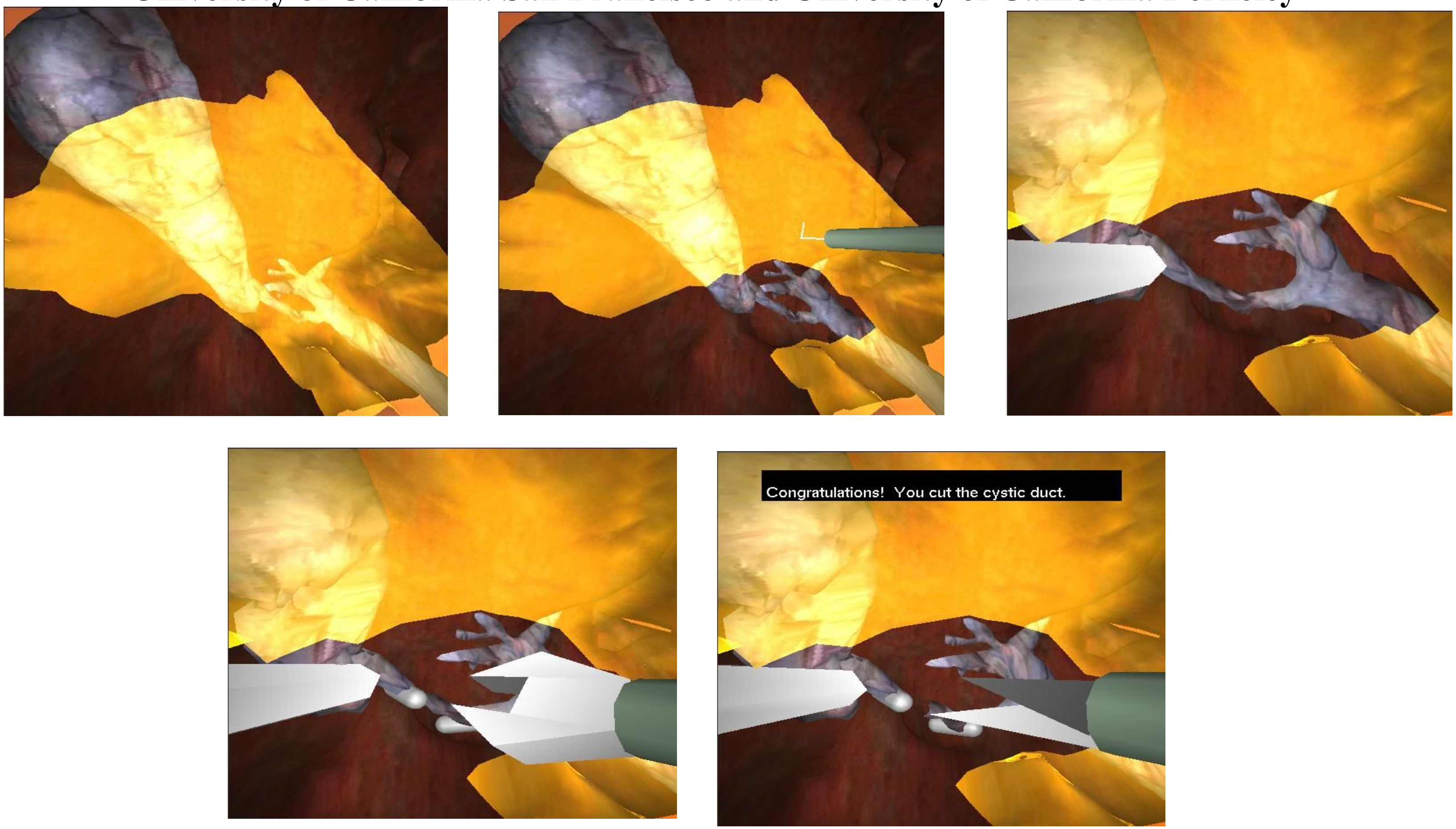
Current Simulation: Gallbladder removal



Cut cystic duct

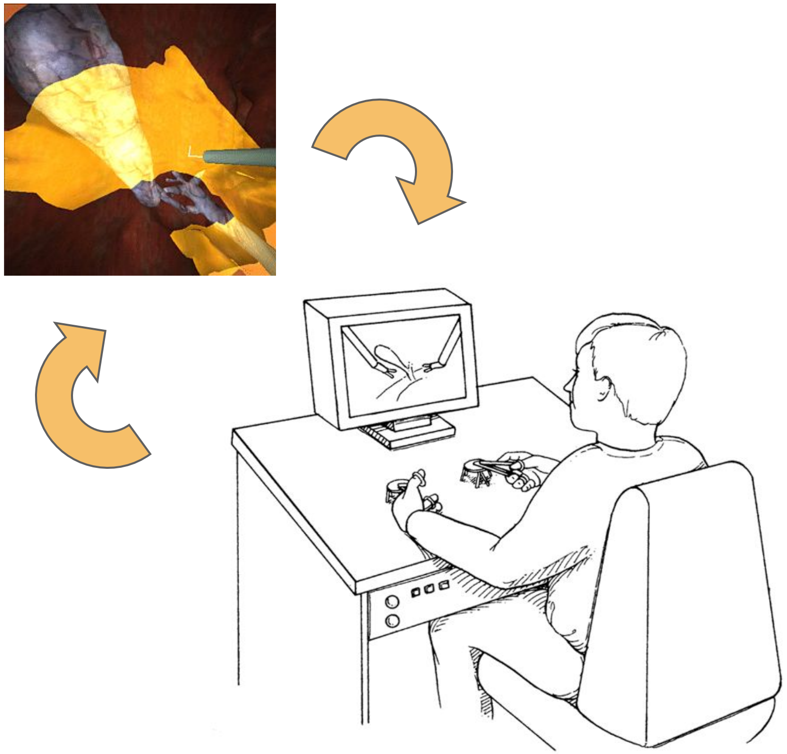
Laparoscopic Cholecystectomy (Gallbladder Removal) Simulation

Frank Tendick, Michael Downes, M. Cenk Cavusoglu, Shankar Sastry, and Lawrence Way
University of California San Francisco and University of California Berkeley



Virtual Environment Based Surgical Training Simulator Concept

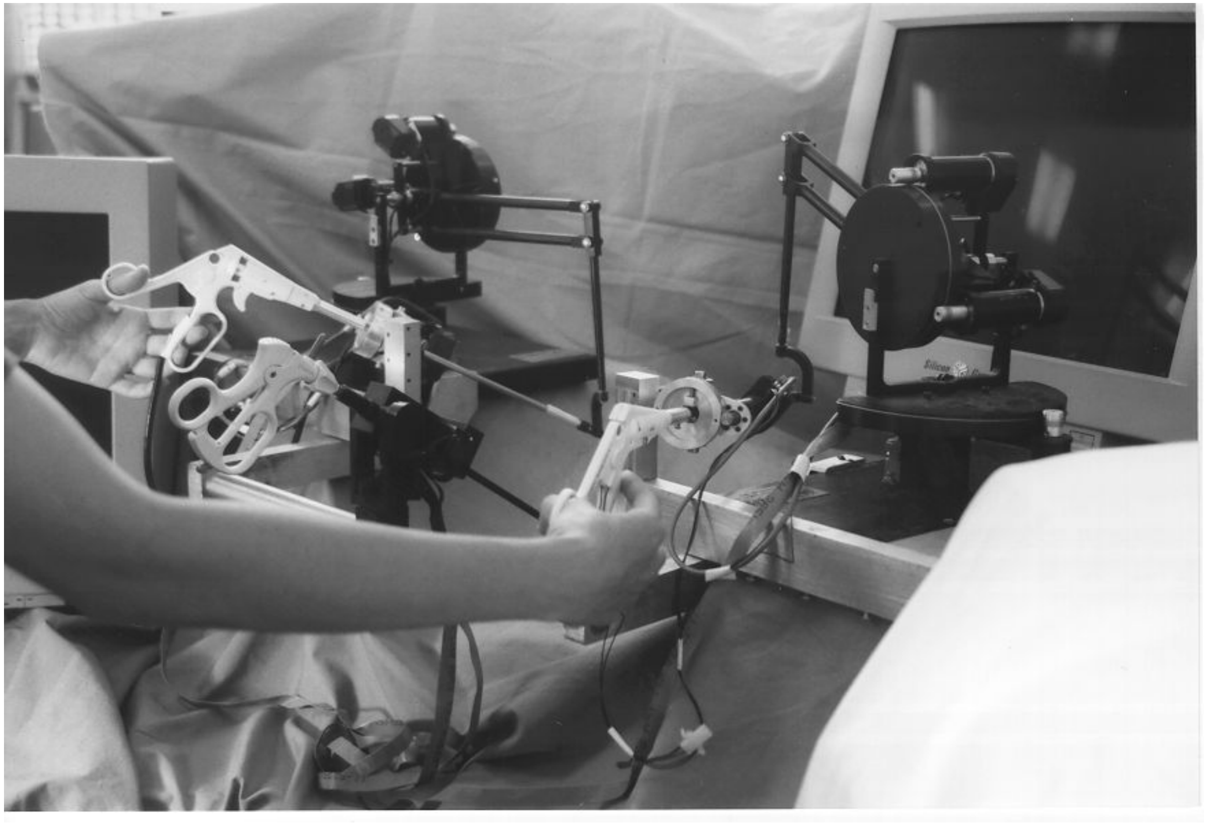
- Arbitrary anatomies and pathologies
- New techniques
- No risk to a patient
- Standardization of training and accreditation



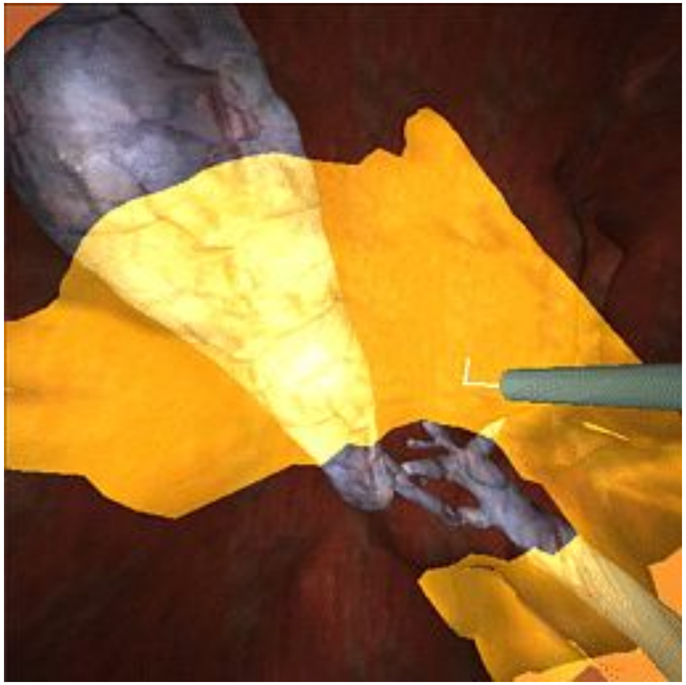
Research Problems

- Realism
  - Computer graphics
  - Deformable object models
  - Haptic interaction
- What to teach
  - Basic motor skills
  - Spatial skills
  - Tasks and procedures
- Verification of skill transfer from training simulator to real surgery

Training Simulator - Hardware



Training Simulator –
Teaching Tasks and Procedures



Haptic Interfacing to Virtual Environments

- Stability of haptic interaction with virtual environments
- Simulation of stiff walls
- Haptic rendering of surface texture
- Haptic interaction with deformable bodies

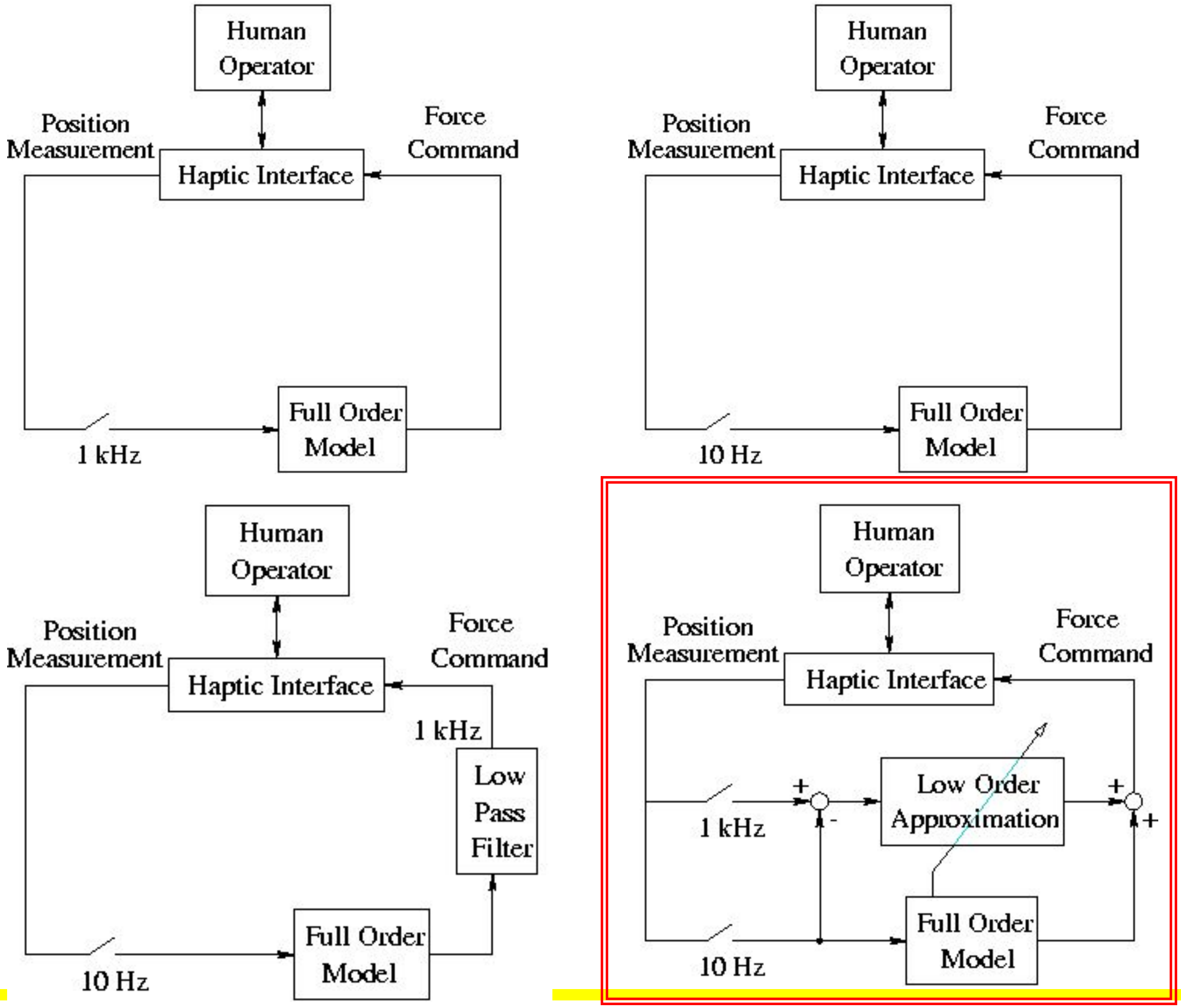
Haptic Interaction with Deformable Bodies

- Deformable bodies are simulated with very high order dynamical models

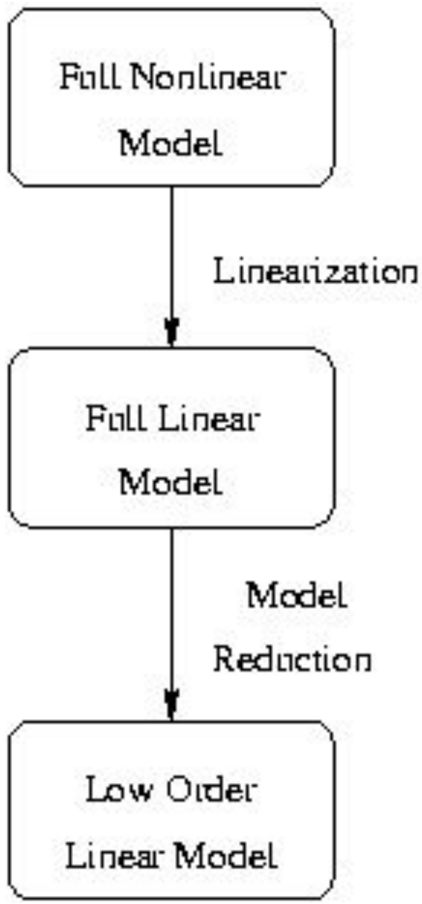
- Haptic interaction require bandwidth of ~1kHz, but these high order models can only be simulated at ~10Hz

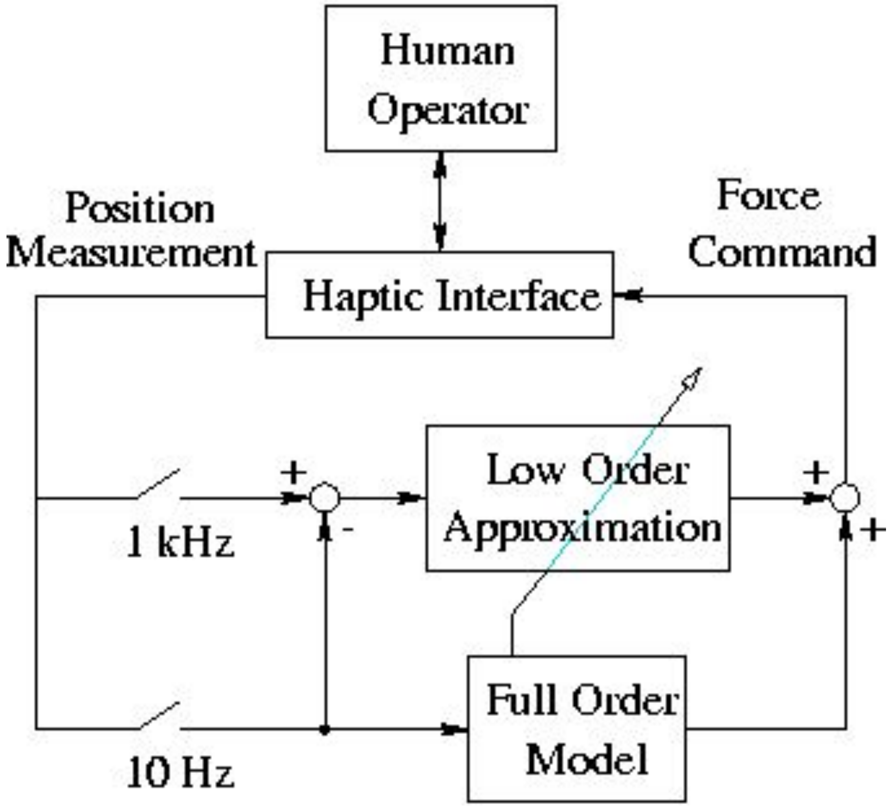
- This affects the stability and fidelity of interaction

Simulation Schemes



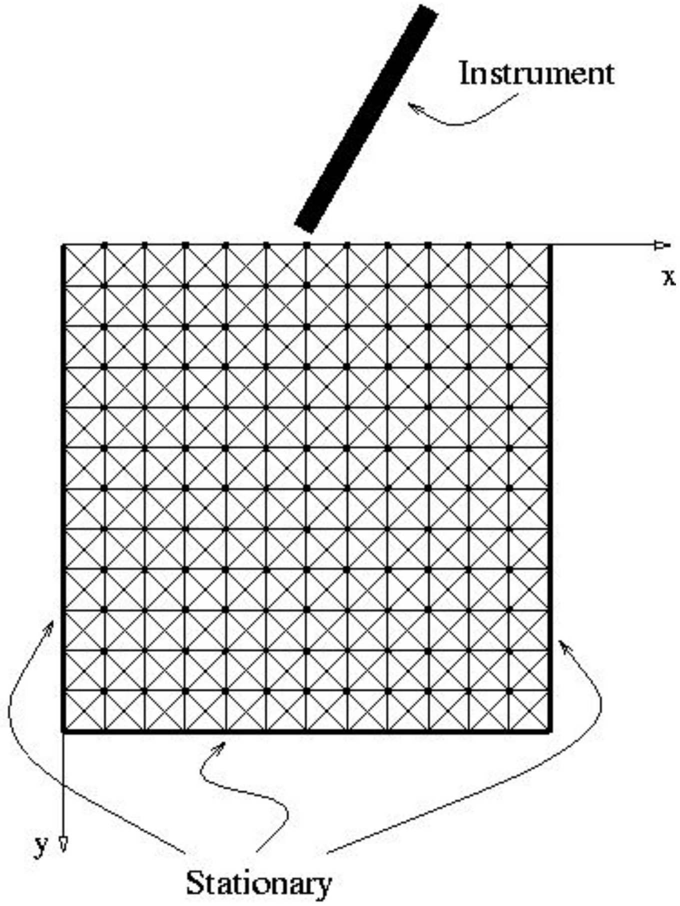
Low Order Linear Approximation to Model Intersample Behavior



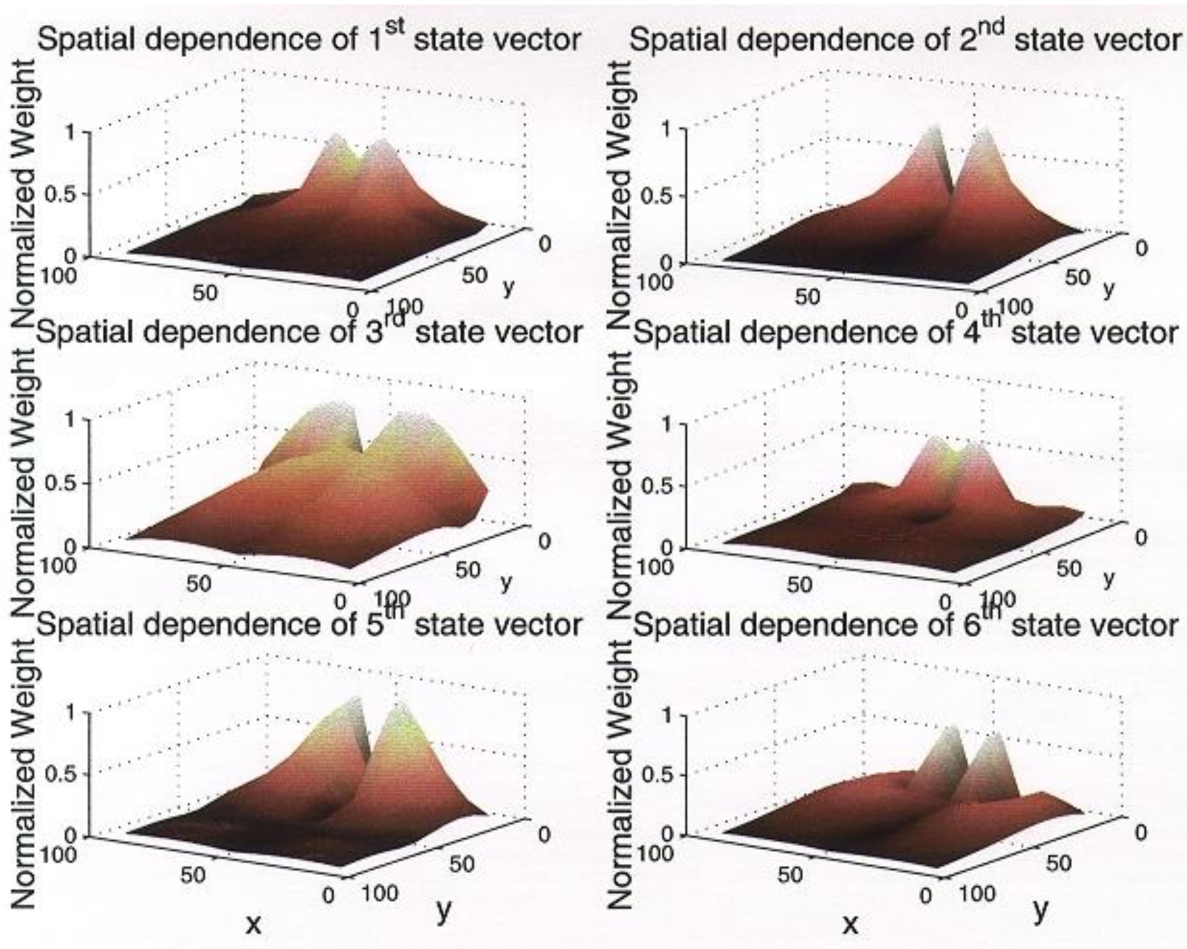


Model Reduction

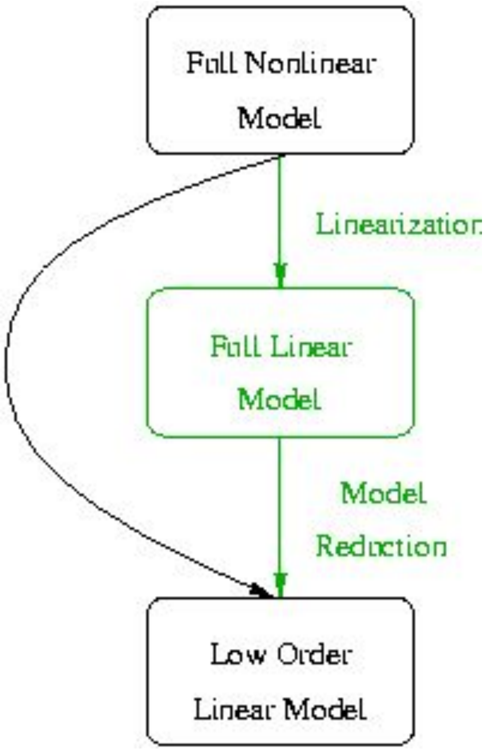
- 12x12 2-D lumped element model
  - 2 input 2 output dynamical system
  - 524th order dynamics
- Balanced model reduction
  - 10th order approximation with less than 1% error

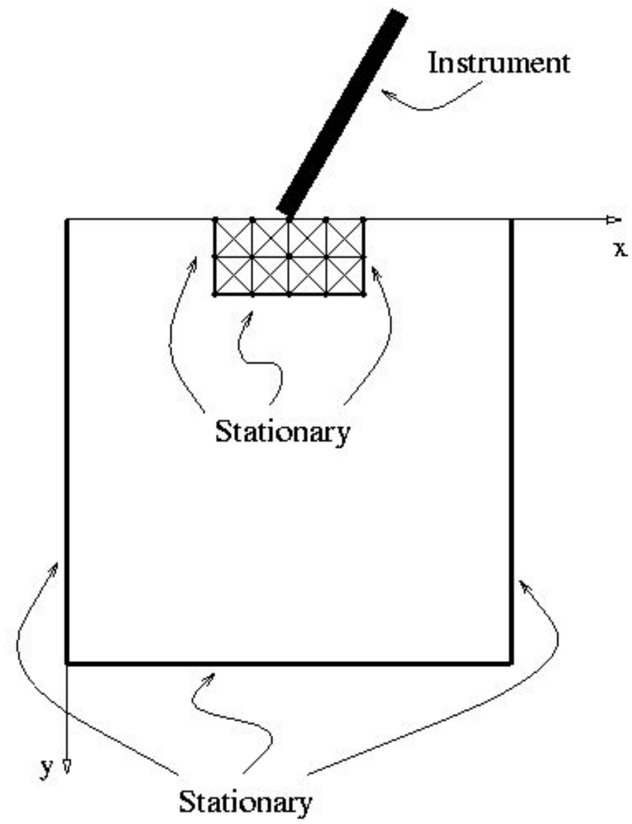


Reduced Order Model is a Local Approximation



Constructing a Local Model in Real Time



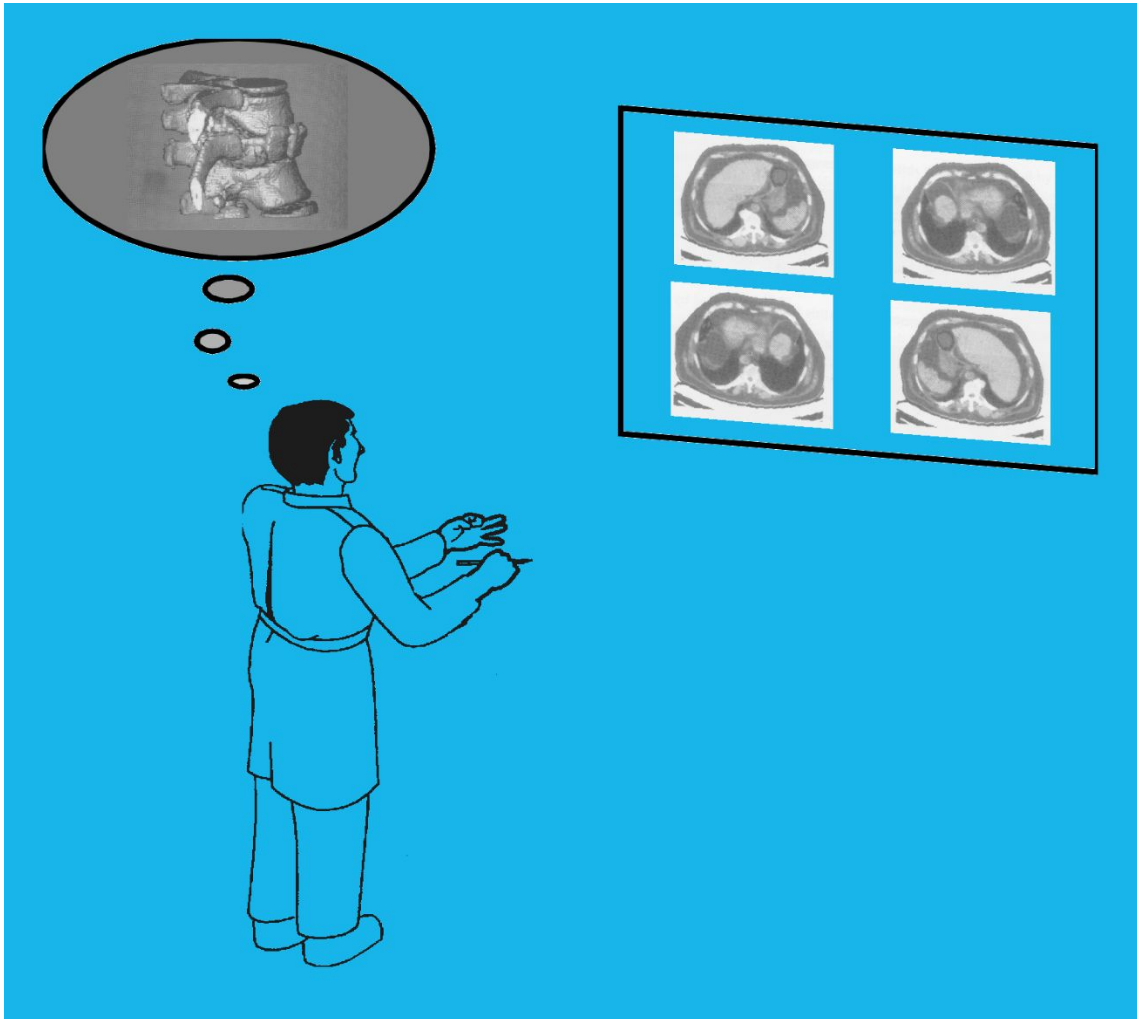


Integration and Telesurgery

Imagine a surgeon operating on an injured sailor with shrapnel embedded near the spine, using current technology:

- **CT image slices show the relationship between the shrapnel and surrounding tissues, but only in 2-D plane sequences**
- **The surgeon must create a mental model of the 3-D relationships in his or her mind**
- **As the surgeon operates, tissue deforms and relationships change, increasing the difficulty**

Integration and Telesurgery



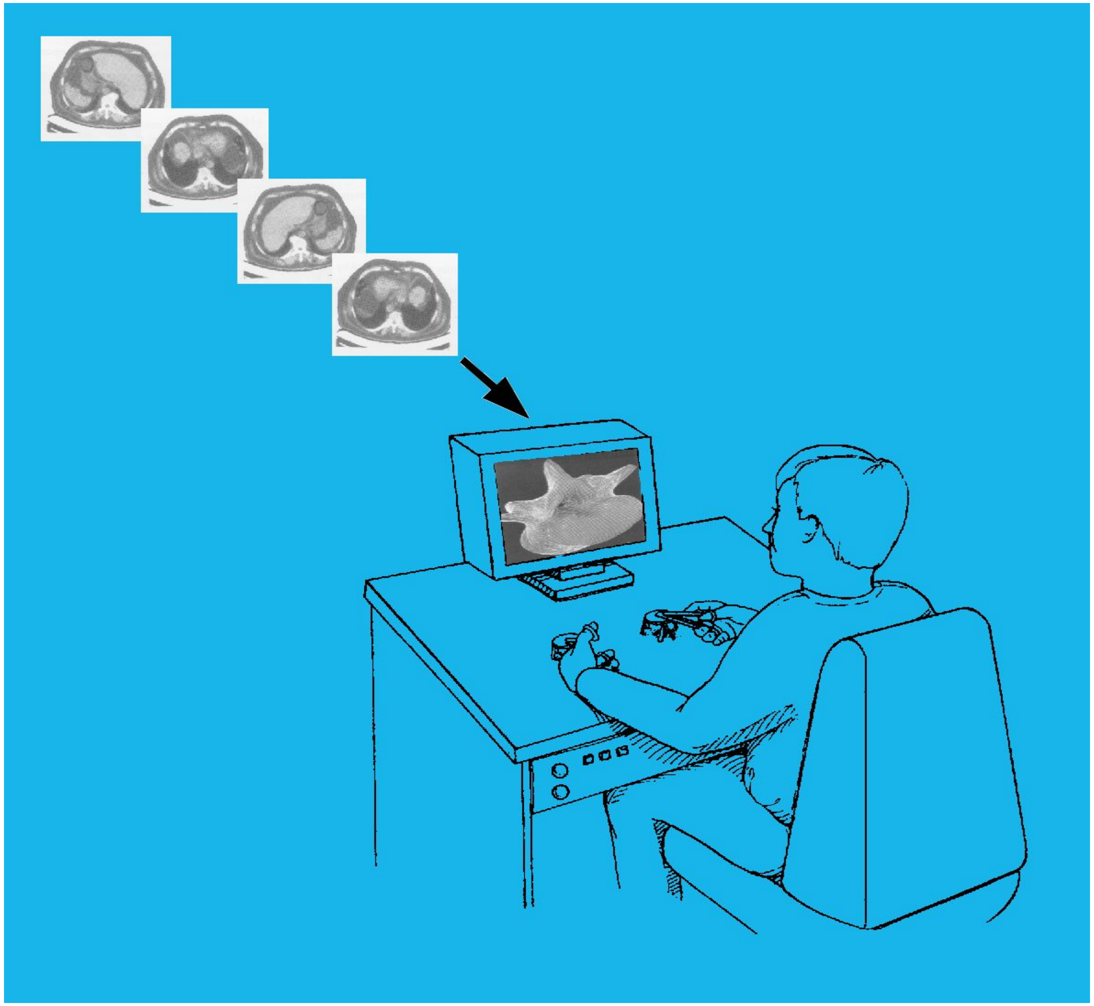
Surgeon viewing 2-D image slices must construct 3-D mental model

Integration and Telesurgery

Now imagine the surgeon with the ultimate visualization technology:

- **CT images are segmented and reconstructed in 3-D**
- **The surgeon can view the reconstructed model using an autostereographic display, manipulate simulated tissues, and consult another surgeon (local or remote) simultaneously viewing the model**
- **The surgeon practices the procedure in a virtual environment, operating on the model**

Integration and Telesurgery

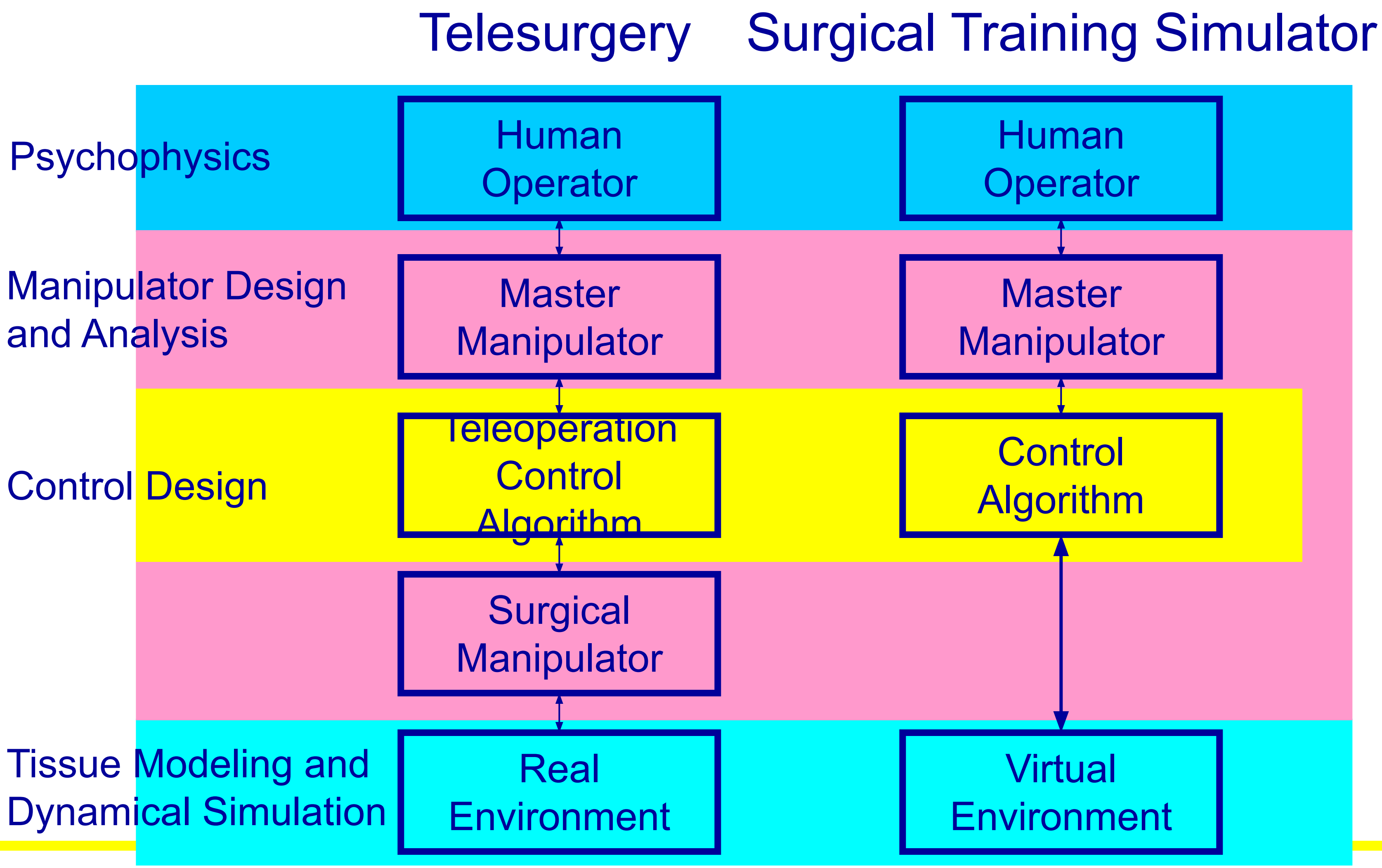


Reconstructed, animated model can be used for simulation, consultation with a remote expert, or to establish spatial relationships during the operation

Surgical Simulation – What is Next ?

- **Deformable tissue models for dynamic simulation**
  - Fast – simulated in real time
  - Interactive – haptic interaction
  - Realistic – visually and haptically realistic

Summary



Telesurgery
Surgical Training Simulator
Psychophysics
Manipulator Design and Analysis
Control Design
Tissue Modeling and Dynamical Simulation
Human Operator
Master Manipulator
Teleoperation Control Algorithm
Surgical Manipulator
Real Environment
Human Operator
Master Manipulator
Control Algorithm
Virtual Environment

Summary

	Telesurgical Workstation	Surgical Training Simulator
Control Design and Evaluation	• Controller design • *In vivo* suturing and knot tying tests • Quantitative evaluation	
Haptic Interfacing	• Design of optimal controller for soft tissue manipulation • Experimental determination of performance requirements	• Bandwidth requirements • Local linear lower order approximation
Deformable Tissue Modeling		• Real-time finite element analysis • Lumped element versus finite element models • Suturing simulation

Continuing Research Topics

- **Telesurgical Workstation**
  - Force feedback
  - User interface
  - Complete surgical operation
- **Haptic Interface**
  - Time delay
  - Human perception experiments
- **Tissue Modeling**
  - Parallel implementation
  - Nonlinear tissue behavior
  - Cutting and realistic tissue - instrument interaction

Future

- Telesurgery
  - Smaller scale manipulators for cardiac and fetal surgery
  - Critical look at the mechanical design of teleoperation systems from control point of view
  - Surgery on the beating heart
- Surgical Simulation
  - Deformable tissue models for dynamic simulation
  - Bridging the gap between finite element, finite difference, and lumped element models, i.e. computer scientists and mechanical engineers

Robotic Surgery Companies Today

- Intuitive Surgical, 2014, Da Vinci
- Stryker, 2013, MAKO (knee and hip surgery)
- Accuray, Cyberknife, partnered with Kuka (radiation therapy)
- Smith & Nephew, NAVIO, knee replacement
- Mazor Robotics, 2012, Mazor X, neurosurgery
- Auris Health, MONARCH robotic bronchoscopy (now J&J)
- ….

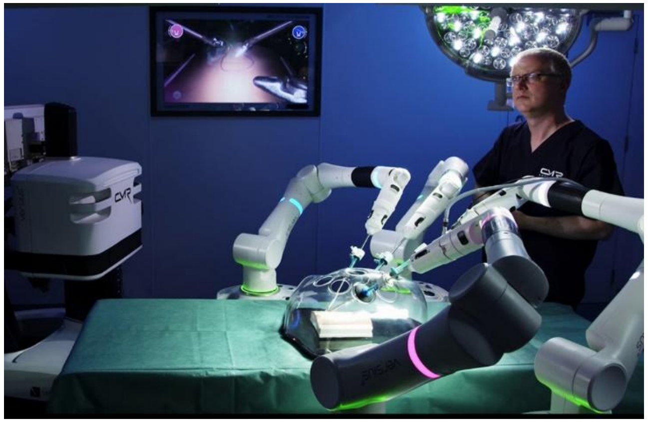
Intuitive Surgical Da Vinci System
https://intuitive.com

- As minimally invasive surgery expands, Academic Medical Centers will continue to play a large role in preparing the surgeons of tomorrow for its latest modalities, including da Vinci robotic-assisted surgery.
- There are currently 350+ da Vinci systems spread across 140 robotics programs in U.S. Academic Institutions, which help 90,000+ patients every year.[1]

Auris Monarch J&J Bronchiboscopy System

- For remote insertion of Bronchioscopes.
- Especial need for Covid
- Can it be made less expensive?

Newer Companies



Clockwise from bottom left

1. ActivSight by ActivSurgical: soft tissue suturing
2. Versius by CMR Medical, laparoscopic procedures
3. Dexter by Distal Motion, laparoscopic procedures

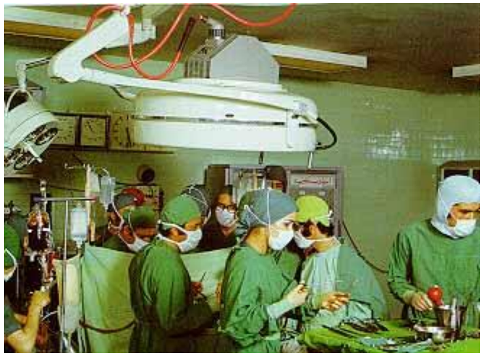
The Digital Human: Building a Community

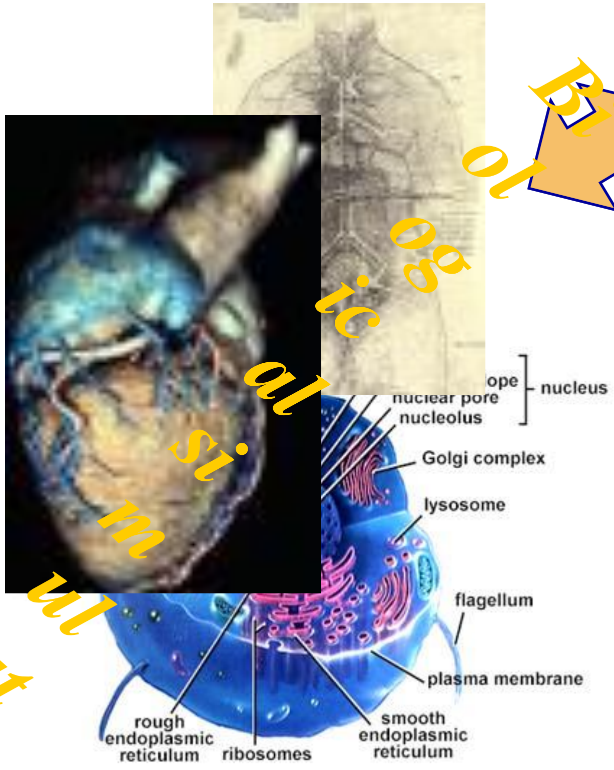
Shankar Sastry &
Kay Howell, Henry Kelly, Gerry Higgins (NLM)
Federation of American Scientists

Biomedical Simulation Contexts

Emergency Response

Treatment protocols





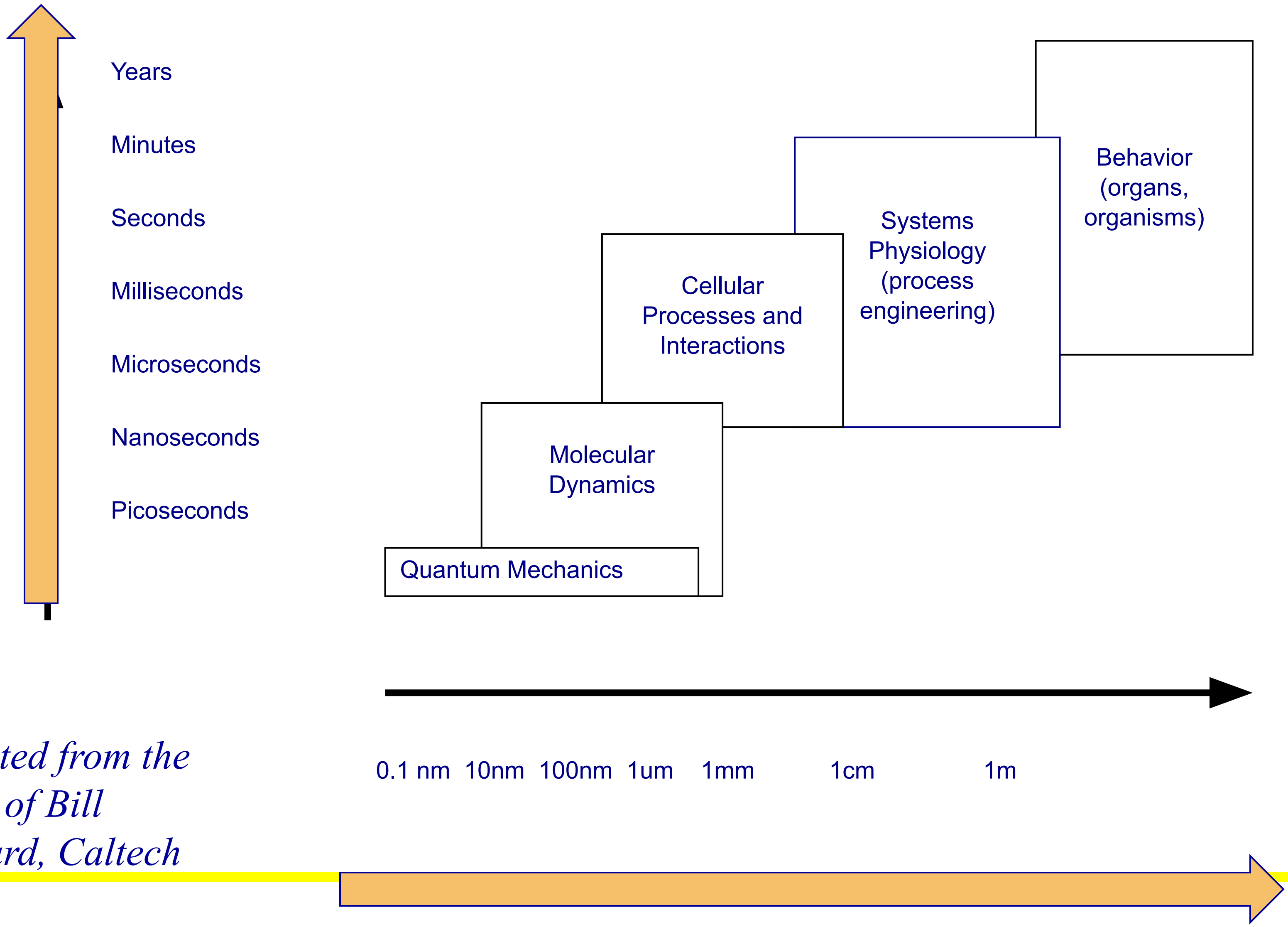
Epidemiology

Training tools

Digital Human Objectives

- Simulate all relevant physical scales, time scales and stages of development
- Provide logical structure independent of expression in software
- Develop open architecture, platform independent, easy to upgrade
- Allow collaborative, worldwide development and sharing by many individuals and teams

Need for Multiple Scales



Adapted from the work of Bill Godard, Caltech

Scope of Digital Human Ontology

Biological Scale	Structure	Discipline, Classification Efforts	Proposed Initial Reach of Digital Human Ontology
Meters	**Organism**	**Natural history:** ***Little activity***	
Centimeter - Meter	**Organ systems**	**Anatomy:** ***Almost no activity (1-2 studies)***	
Centimeters	**Organs**	**Anatomy:** ***Almost no activity (1-2 studies)***	
Millimeters - Centimeters	**Organ components**	**Anatomy:** ***Some activity in brain, other structures***	
Millimeters - Centimeters	**Tissues**	**Histology:** ***Some activity in brain***	
Microns	**Cells**	**Cell biology:** ***Great activity***	
Submicron	**Organelles**	**Cell biology:** ***Great activity***	
Nanometer	**Supramolecular structures**	**Biochemistry:** ***Some activity***	**?**
Angstrom - Nanometer	**Molecular: Proteins, genes**	**Biochemistry, molecular biology:** ***Great activity***	**?**
Angstrom & below	**Elemental**	**Physics, chemistry:** ***Some activity***	

Current Rate Limits on Biomedical Simulation

- No interoperability of software components (reaching the limits of cottage industry approaches)
- No interoperability allowing direct links connecting databases and models
- Difficulty of extracting measurements from published papers (specification)
- No community to provide next-generation publication (peer review, bug reports, validation, version control)
- Confusion over intellectual property

Design Goals

- Broadest possible community of developers
- Rigorous review and validation
- Valid, straightforward path to primary data sources
- Encourage creative, competing solutions
- Highest possibility compatibility with existing models
- Rooted in biology -- no forced programming artifacts
- Minimize bureaucratic and computational overhead
- Continuously adaptable to discoveries

The Community