An Overview of the Telesurgical Workstation Project

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Key Collaborators: Frank Tendick, Ron Fearing

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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
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
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<td>Master Manipulator</td>
<td>Teleoperation Control Algorithm</td>
<td>Slave Manipulator</td>
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<td>Real Environment</td>
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<td>Virtual Environment</td>
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</tbody>
</table>

**Overview**

Telesurgery

- Human Operator
- Master Manipulator
- Teleoperation Control Algorithm
- Slave Manipulator
- Real Environment

Surgical Training Simulator

- Human Operator
- Master Manipulator
- Control Algorithm
- 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
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.
Next Generation End-Effector

• Streamlined -- No Snagging at Canula
• Shorter -- Better Access in Small Spaces
Haptic Human Interfaces

- 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

Surgical master stylus will include a finger masters with a stereo tactile display unit.
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.
1997 Prototype Telesurgical Workstation

Surgical Master

Positioning Robot

Laparoscopic Manipulator
Telesurgical Workstation: Schematic

Two sub-systems:

- **Master**
  An off-the-shelf six degree of freedom haptic interface, with three channels of force-feedback

- **Slave 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 master 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 laparoscopic monitor, the surgeon moves the master’s stylus, thereby positioning the slave robot.
**Slave 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.
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!
Bilateral Teleoperation System Design
UCB/UCSF Laparoscopic Telesurgical Workstation
1998 Prototype Telesurgical Workstation

- Surgical Master
- Laparoscopic Monitor
- Gripper Control (foot switch)
- Master Control Computer
1998 Prototype Workstation

ROBOTIC MANIPULATOR

Slave Control Computer

Gross Positioning Stage

Fine Motion Stage
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

• Performance comparison/evaluation

• Complete procedure

ongoing

approved
ANIMAL LAB TRIALS 1998
Suturing with Unimanual System, 1998
Jumpy Joystick?

Joystick Samples
Every 10mS
From Joystick
To Control Loop
Robot Control Loop
Runs Every 1mS

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

“Roll1” 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)**
  \[ x_m = x_s , \quad f_m = f_s \]

- **Transparency (Lawrence)**
  \[ Z_t = Z_e \]

- **Sensitivity to environment impedance changes (Cavusoglu)**
  \[ \text{maximize} \left\| W \left( \frac{dZ_t}{dZ_e} \right) \right\|_\infty \]
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

\[ P = -h_{12}h_{21} \frac{1}{(h_{11} + Z_{hop})(1 + h_{22}Z_e)} \]

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

\[
\begin{align*}
\left| \frac{1}{h_{22}\hat{Z}_e} \frac{Z_e - \hat{Z}_e}{1/h_{22} + Z_e} \right| < |W_{ue}|, \\
\left| \frac{\hat{Z}_{hop} - Z_{hop}}{h_{11} + Z_{hop}} \right| < |W_{uh}|, \\
W_u = W_{ue} + W_{uh} + W_{ue}W_{uh}
\end{align*}
\]

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

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

• Using transparency as fidelity leads to a trivial solution:
  Slave 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:

\[ \left\| W_pS \right\|_\infty \leq 1, \quad W_p(j\omega) = \frac{1}{b(j\omega)} \]

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:

\[ \arg \sup_{\|W_u T\| \leq 1, \text{nom. stable}, \|W_p S\| \leq 1} \left\| W_s \frac{dZ_t}{dZ_e} \right\|_{\infty} \]

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 Training Methods in Surgery

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<tr>
<th>Training Method</th>
<th>Limitations</th>
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<tr>
<td>Apprenticeship</td>
<td>- Limitations due to risks to patients</td>
</tr>
<tr>
<td></td>
<td>- Difficulty in diffusion of knowledge</td>
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<tr>
<td>Textbooks</td>
<td>- Two Dimensional</td>
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<tr>
<td>Training mannequins</td>
<td>- Not very realistic</td>
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<tr>
<td></td>
<td>- Limited variation in pathologies</td>
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<tr>
<td>Animal experiments</td>
<td>- Excessive cost</td>
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<td>- Anatomical differences</td>
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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 –
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
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
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
- Human Operator

Manipulator Design and Analysis
- Master Manipulator
- Teleoperation Control Algorithm
- Slave Manipulator

Control Design
- Control Algorithm

Tissue Modeling and Dynamical Simulation
- Real Environment
- Virtual Environment
## Summary

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<td>Quantitative evaluation</td>
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| 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
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

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

- Interagency Leadership
  - Technical Architecture
    - Databases
    - Unified Ontology
    - Geometry
  - Applications
    - Incident Management and Response
    - Rapid Drug Development
    - Biomedical Research
    - Biological Education and Training
    - others
  - Services and Policy
    - IP license, issues
    - Bug reporting
    - Version control
    - Validation/certification
    - Peer review