Summer School Surgical Robotics
Montpellier, France, 10-Sept-2009

Design of Surgical Robots

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Outline

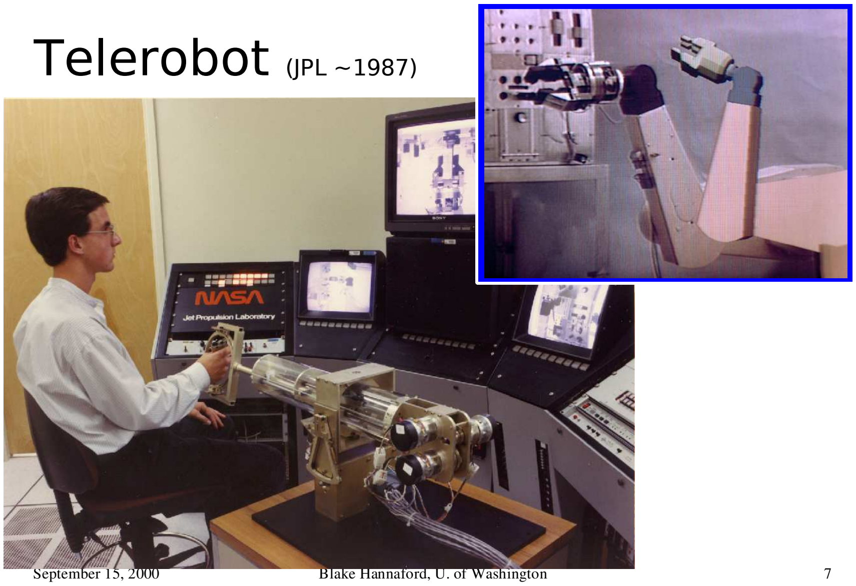
- Telemanipulation history and Concepts
- Surgical Robotics Overview / History
- RAVEN
- HapSMRT
- NEEMO

History

- Nuclear Teleoperators (waldos) 1940's
- Computer controlled telerobots 1980's
- Haptic Interfaces and commercialization 1990's
- Emergence of Medical Telerobots 00's

Ray Goertz

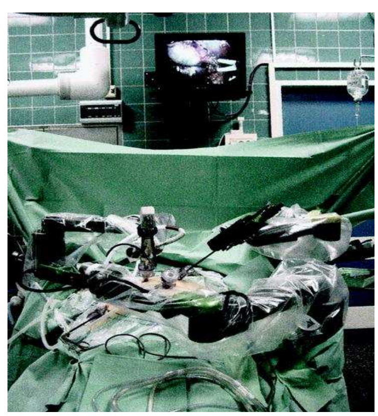
Telerobot (JPL ~1987)



Remote Surgery (2001)

Marescaux

New York



France

Clinical Experience

- ~2003
- Dr. Mehran Anvari
- Southern Ontario to Hudson’s Bay
- Zeuss robot
- Canadian Health Ministry Approval
- 25 patients

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“RAVEN” Surgical Robot

- Goal: surgical care for combat casualties in “golden hour” after trauma.
- Concept: Robot arms remotely controlled by surgeon
- Compact Spherical Mechanism

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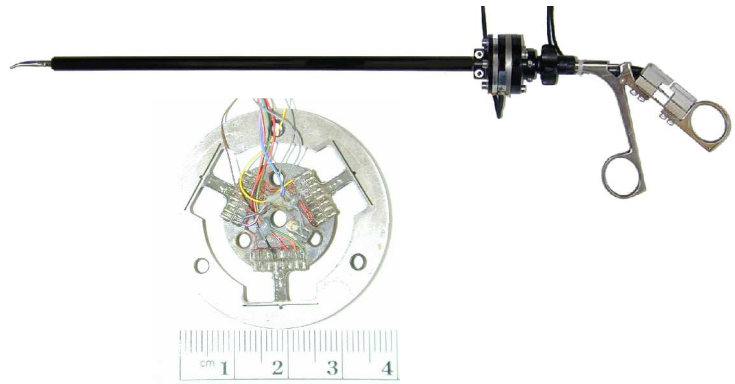
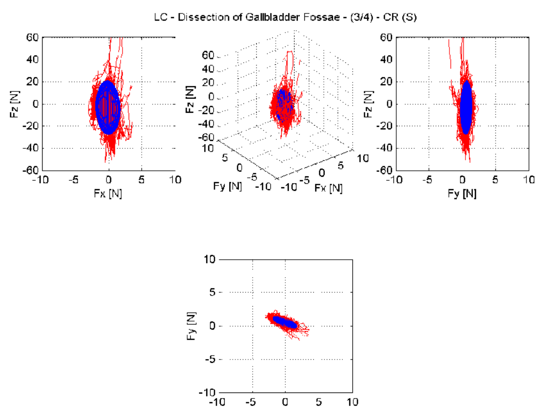
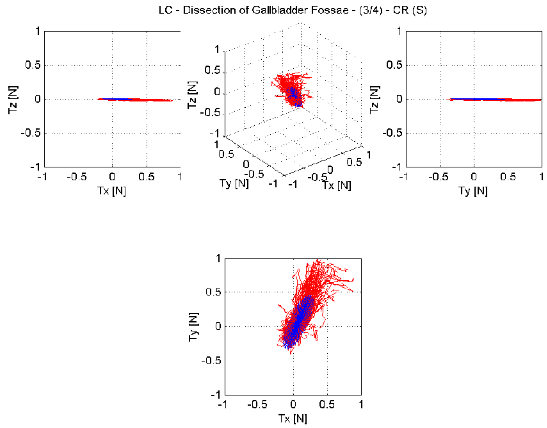
Instrumented Endoscopic Grasper



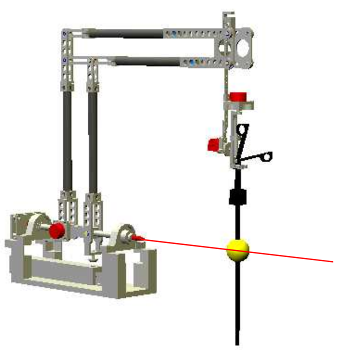
Forces - Raw Data

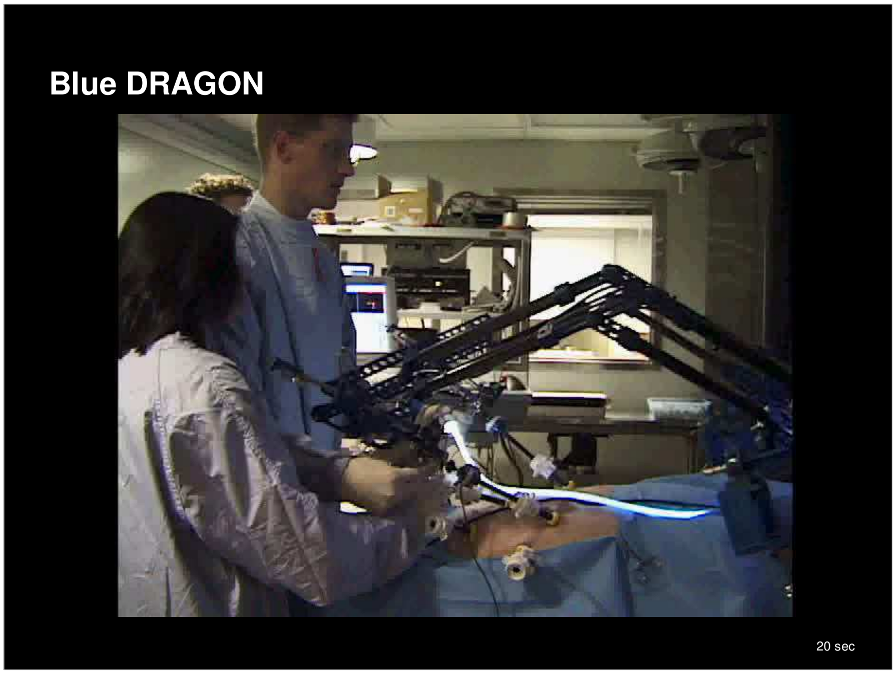


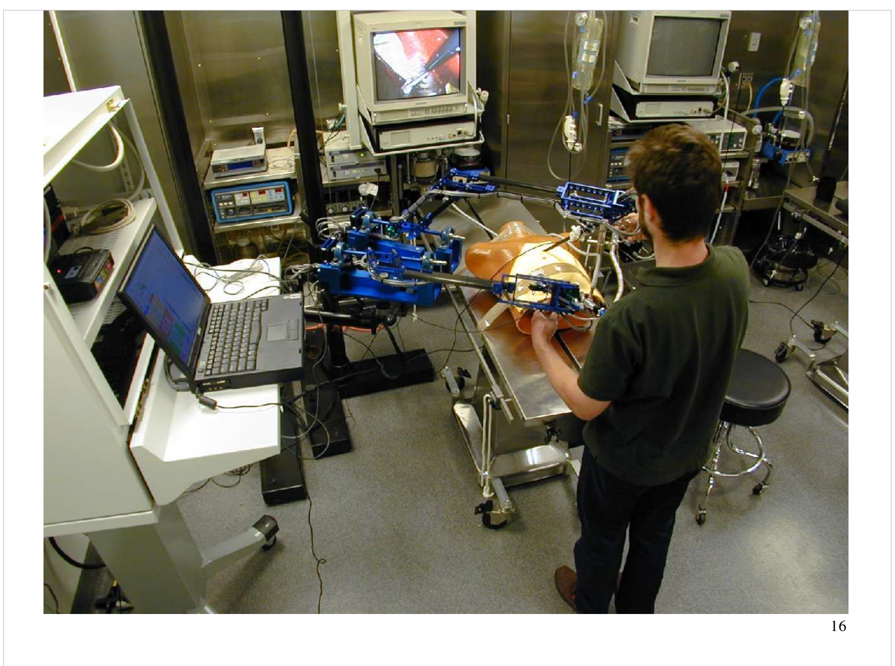
Torques - Raw Data



Blue DRAGON




Blue DRAGON
20 sec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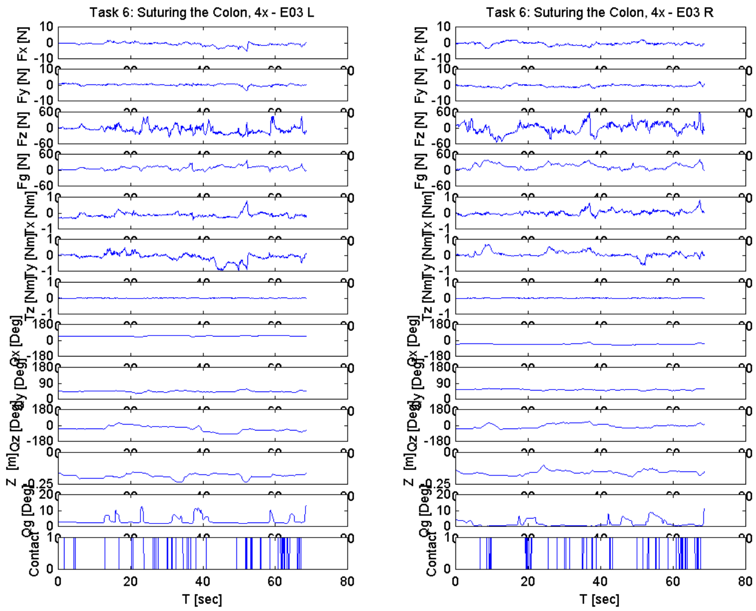

Analysis and Uses of surgical recordings

- Design Specs: e.g. Histograms / PDFs
- Skill Assessment:
  - Hidden Markov Models
  - Markov Models
  - Train HMMs of each skill cohort
- Procedure tracking
  - Identify completion of sub-procedures
  - Catch errors?

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Surgical Robot Project – Design Goals

- Develop a smaller, more dexterous surgical robot.
- Aim to provide force feedback to surgeon.
- Increase its mobility and ability to operate on its own.
- Evaluate in experimental surgery (porcine model)

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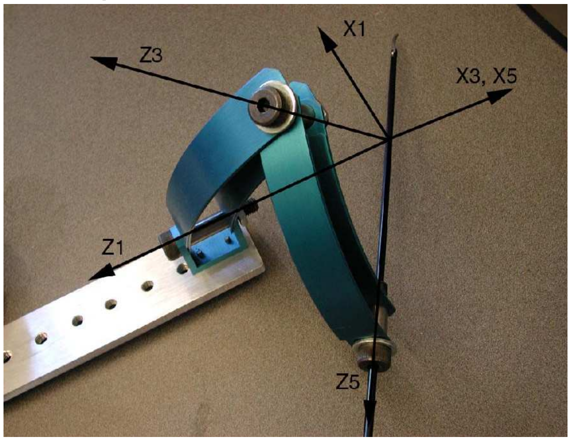
Spherical Mechanism

- Axes intersect at port
- Compact



Design Optimization Goals

- Design Freedoms: 2 link angles
- Must reach measured Extended Dexterous Workspace (90deg)
- Must have good isotropy in Dexterous workspace (60deg).

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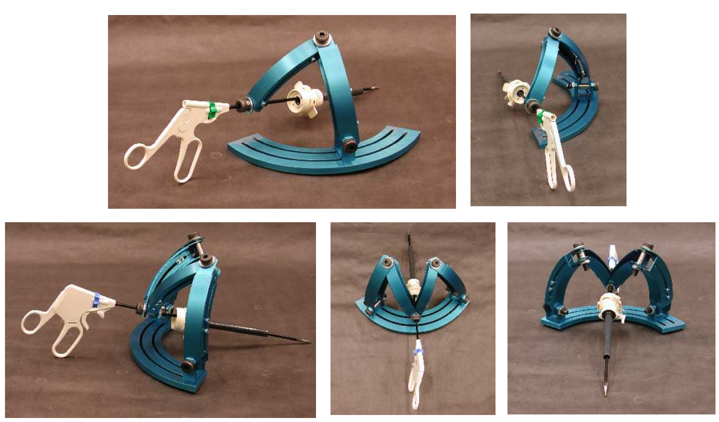
Serial vs. Parallel *Smackdown!*



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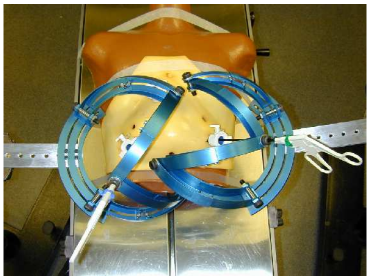

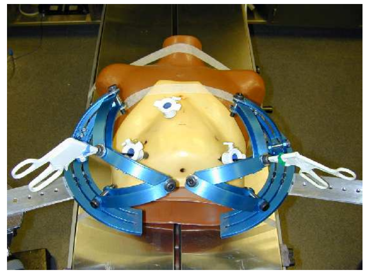

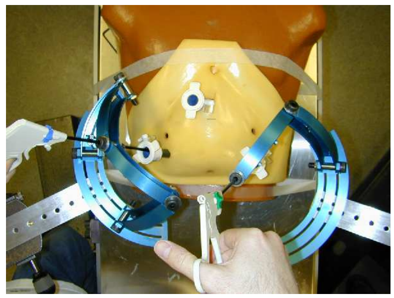

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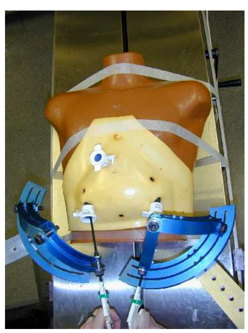

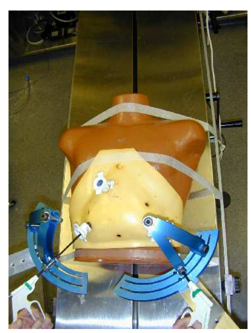

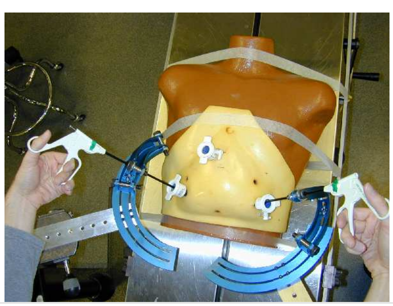

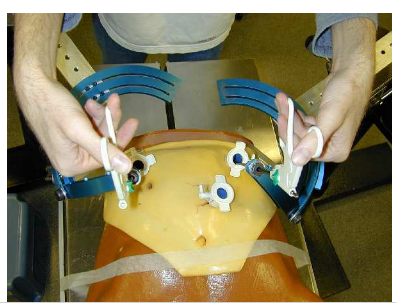

Serial Mechanism Isotropy

- Isotropic – good motion properties in all directions
- Inverse of Jacobian Matrix condition number
- 0 < Isotropy Score < 1
  - Each point in workspace has an Isotropy Score
  - Score = 0: can move in one direction but not another
  - Score = 1: can move equally well in all directions

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Mechanism Isotropy

- Isotropic – good motion properties in all directions
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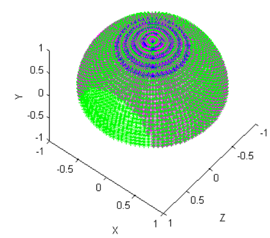
Optimization for Laparoscopy

- From Blue Dragon Experiments – 95% of surgeon motion falls within 60º cone
- Optimize mechanism over surgeon's workspace instead of entire hemisphere



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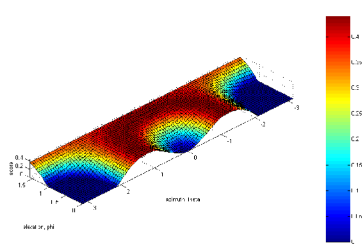
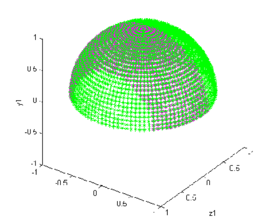
Serial - 60º link angles



Isotropy versus azimuth and elevation



Points with Isotropy> 0.3

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$$S_{sum} = \underset{K}{MAX}\left(\sum_{k^p_{\sigma,\zeta}} ISO(\theta_1,\theta_3) * A(\sigma,\zeta)\right)$$

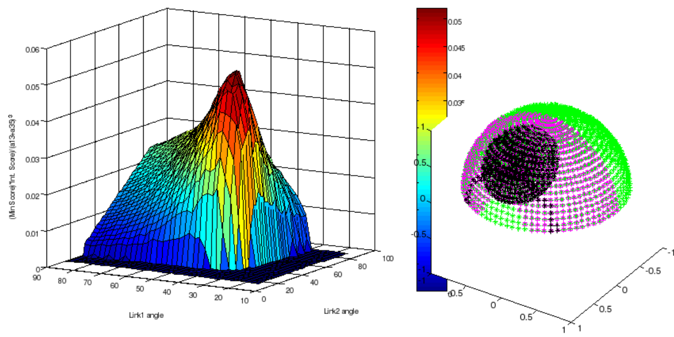
$$S_{min} = \underset{K}{MAX}\left(\underset{k^p_{\sigma,\zeta}}{MN}\left(ISO(\theta_1,\theta_3)\right)\right)$$

$$\varphi(\alpha_{13},\alpha_{35}) = \frac{S_{sum} \cdot S_{min}}{(\alpha_{13}+\alpha_{35})^3}$$

Results

Serial

DWS (60º cone) – Best Design: α_{13}=52º and α_{35}=40º



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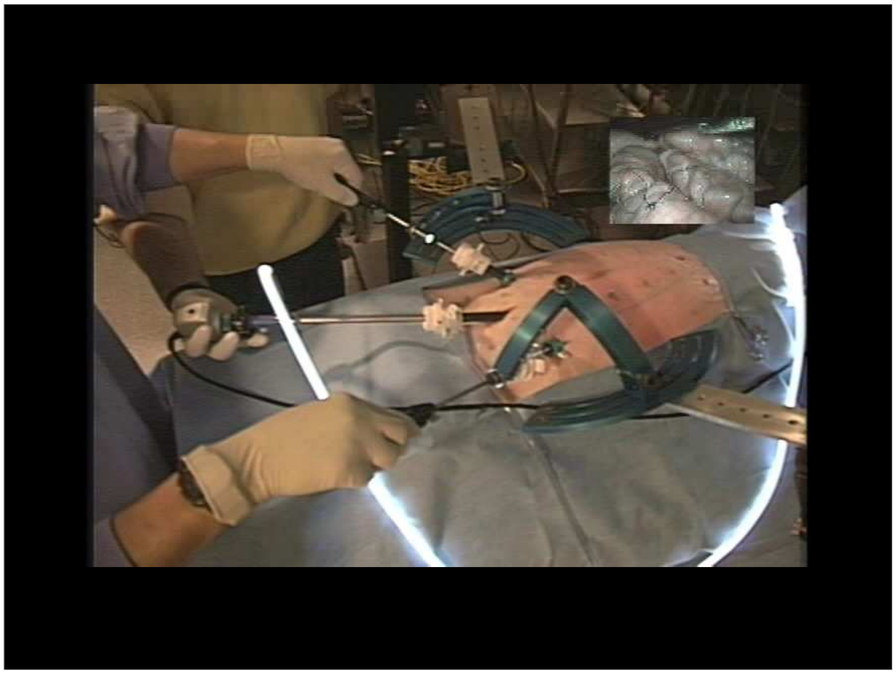

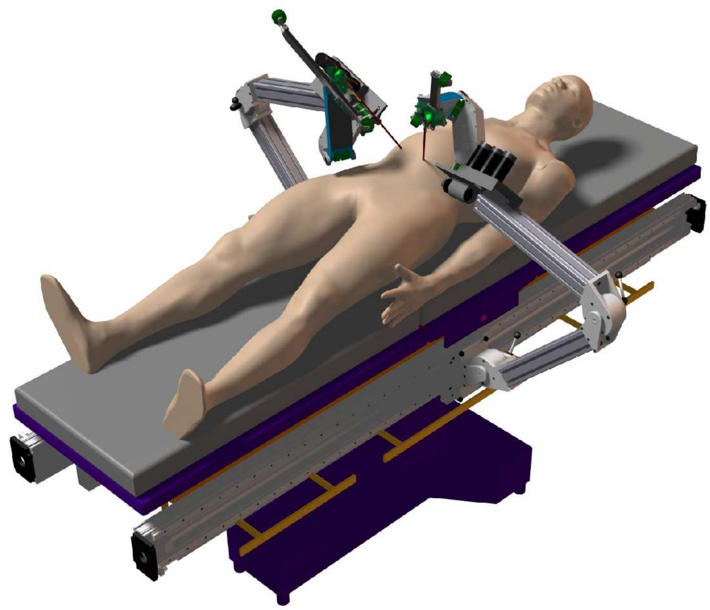

Current Prototype

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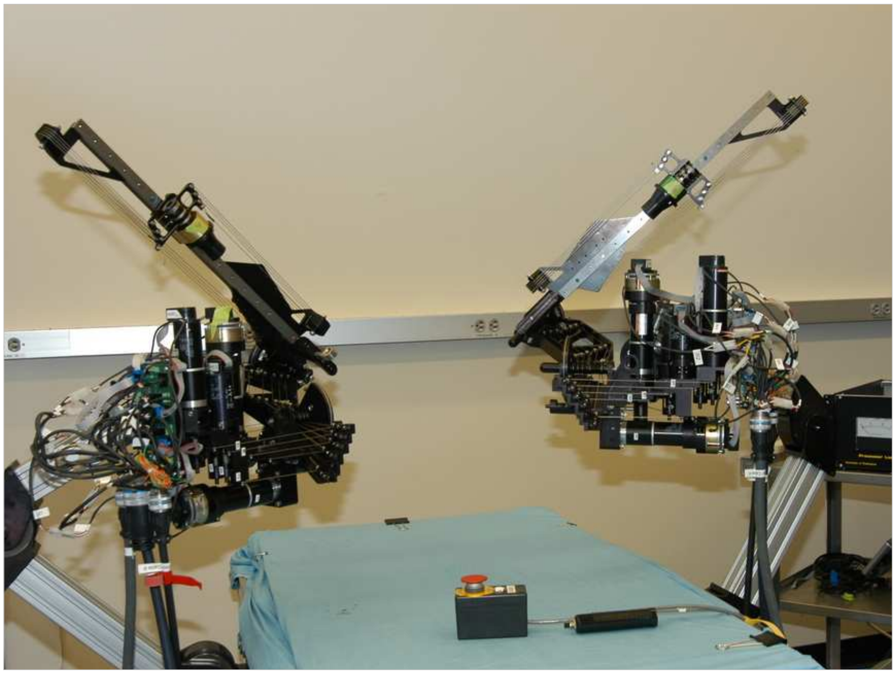

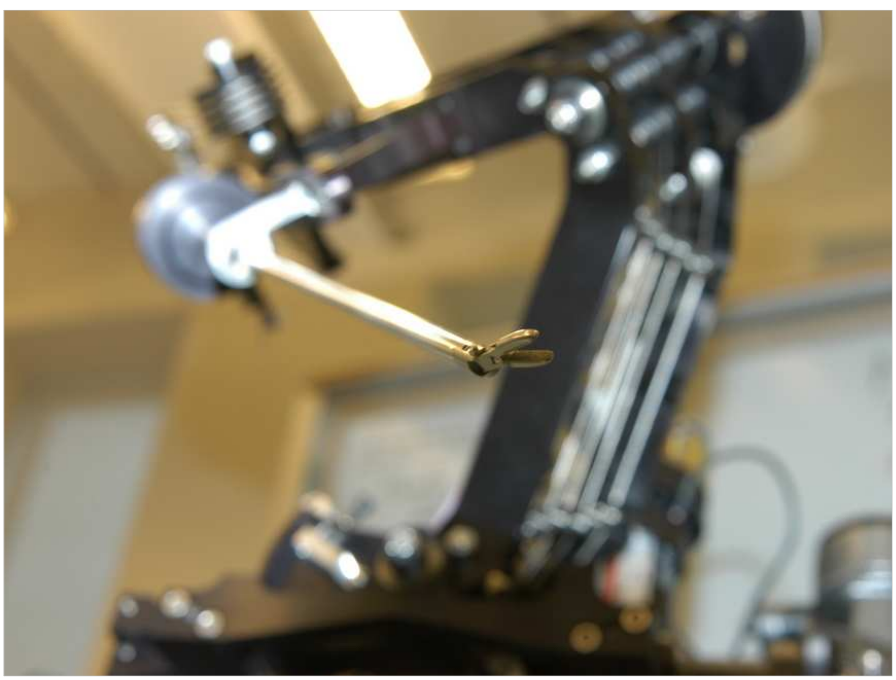

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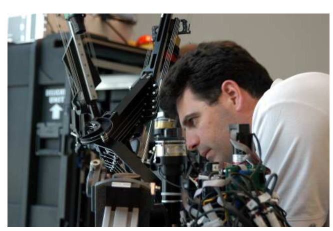

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Controller Box A
USB
GND / +5
Encoders
Hall Sensors
Motor Windings
DC Power

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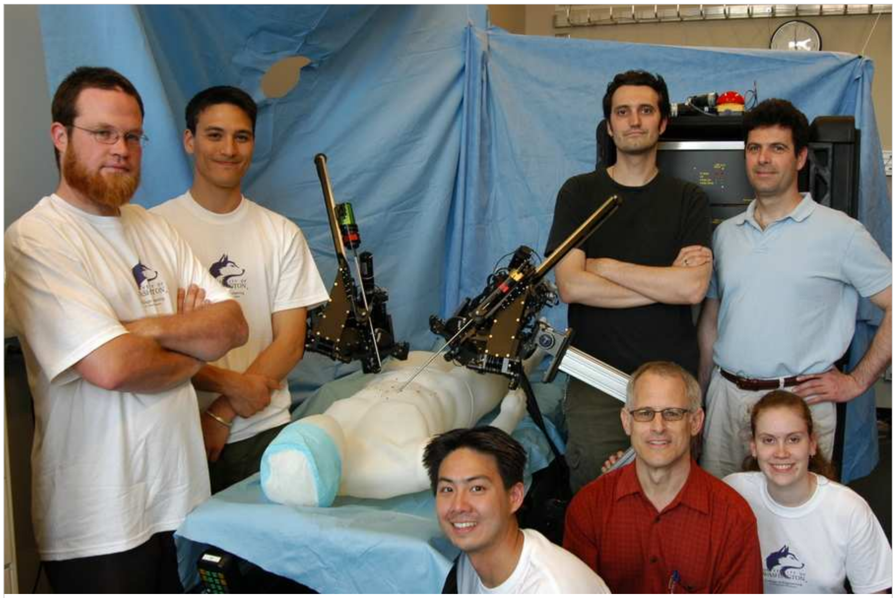

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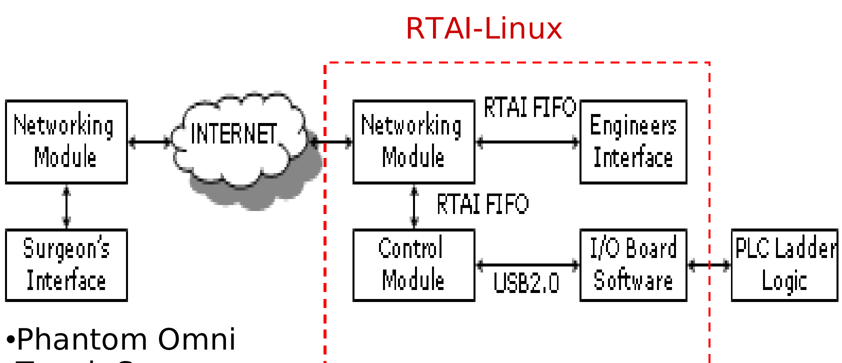
Remote Operation Architecture



- Phantom Omni
- Touch Screen
- Foot Pedal

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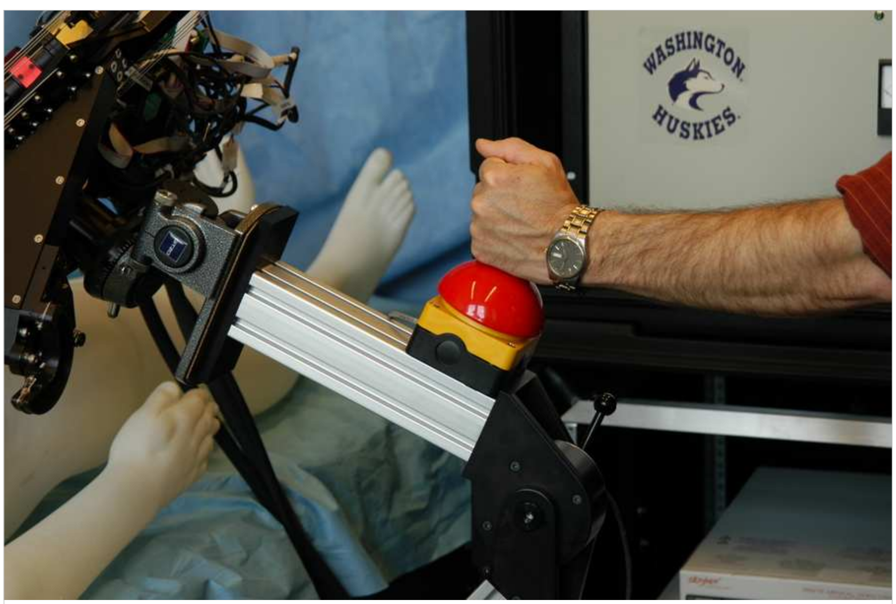
Software Architecture

- Modular architecture based on standard data structures.
- 1000Hz real-time control based on RT-AI Linux
- Internet Protocol between master/slave
- PLC based safety/E-stop processor with 4 states.



Safety Goals

- Reliable robust use for animal experiments.
- Reduce false alarms
- Prevent damage to equipment and tools
- NOT human rated

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Safety System Principles

- Use simple, robust logic and hardware.
- Support a hardware E-Stop
- Keep surgeon in control for any software action.
- Reduce risk due to software complexity

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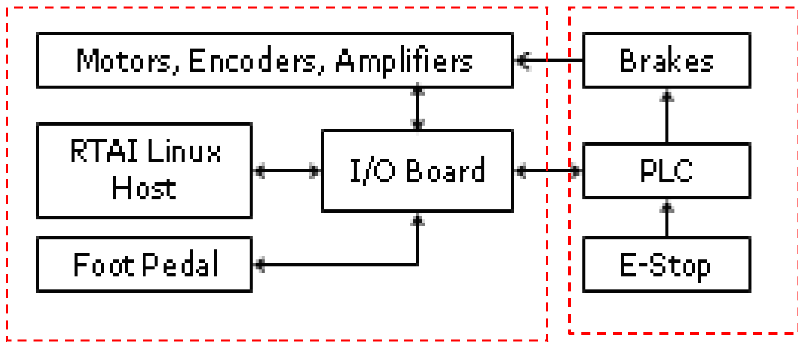
Control Architecture

Control and actuation Safety System



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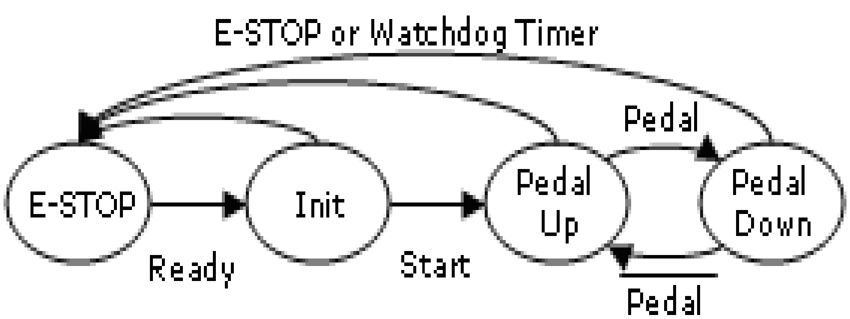
Safety States



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Safety System Implementation

- Programmable Logic Controller (PLC) implements all state transitions
- Linux sends heartbeat signal
- PLC implements watchdog timer
- Linux s/w follows PLC state transitions.
- E-stop state cuts motor power and applies brakes.

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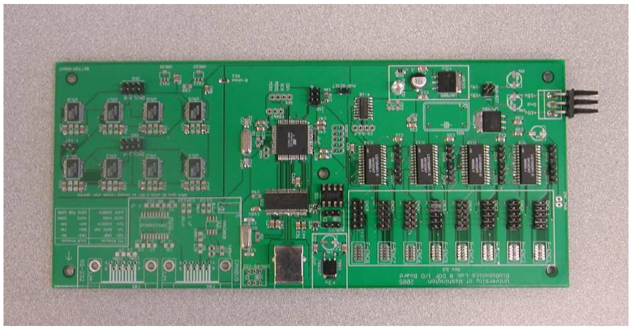

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Portable Surgeon Side Console

- Hardware
  - PC laptop
  - Two Omni haptic device
  - USB foot pedal
  - Video display (NTSC and PC Video)
- Software
  - SSS (surgeon site software)
    - * SGUI (surgeon's graphical user interface)
    - * HDC (haptic device client)

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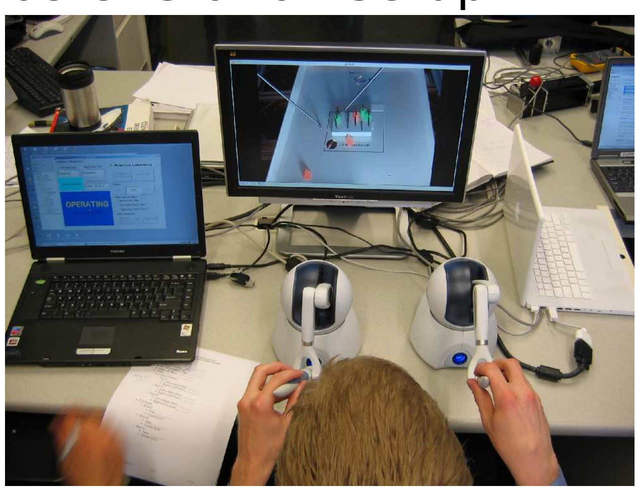
Master Station Setup



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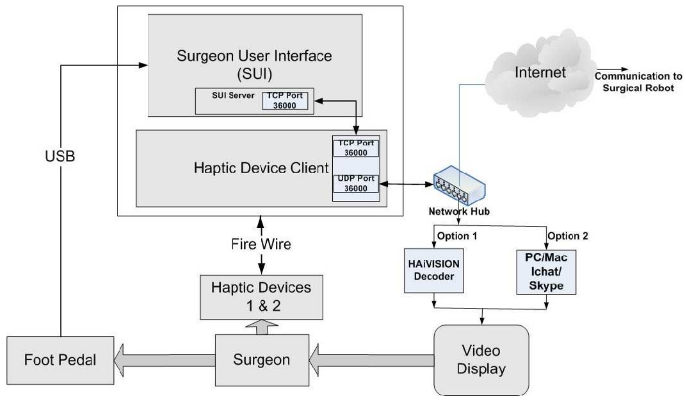
Functional Block Diagram



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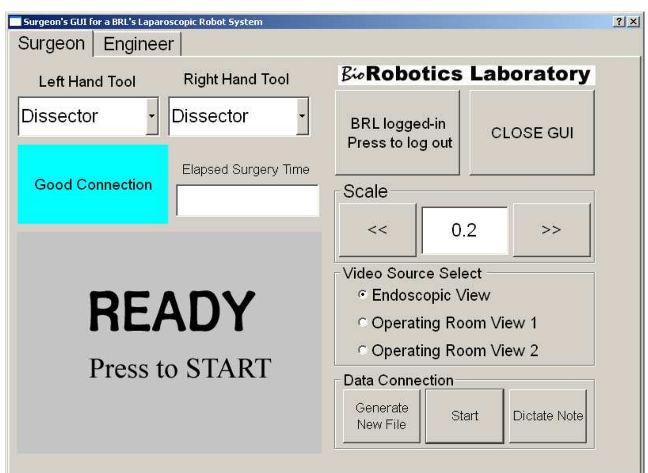
SGUI



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SGUI

- Allows execution of high-level commands
- Written using Qt 4.1.2 from Trolltech, Inc.
- Surgeon tab
  - Allows setting
    - Scale factor
  - Status display (System status)
  - Tool selection (For future)
- Engineer tab
  - Remote IP address of surgical robot

HDC

- Haptic device client
  - Sends commands to surgical robot
    - Position increments – micron units
    - Orientation increment – micro-radians units
    - Use UDP for data communication
      - Low overhead
      - Fast
  - Haptic device mapping
    - Mapping of Haptic Interface Device (HID) to the motion of surgical robot
      - Pitch is mapped to tool wrist
      - Roll is mapped to tool shaft roll
  - Indexing
    - Allows surgeon to operate within the comfortable workspace of Omni
    - Foot pedal is used to engage indexing

Communication Protocol

- UDP packets
- 100-1000 packets per second
- Incremental motion commands

Data Packet Structure

```
typedef struct {
unsigned int sequence;
int c_timestamp;
int s_timestamp;
int delx[2];         // microns
int dely[2];
int delz[2];
int delyaw[2];       // micro-rad
int delpitch[2];
int delroll[2];
int buttonstate[2];
int footpedal;
int checksum;
}masterToRobot_data;
```

Video Feedback

- Desirable Features
  - Video picture quality
  - Low encoding/decoding latency
  - Robustness to network jitter, loss
  - Low cost
- Current Alternatives:
  - HaiVision Hai 500 hardware codec
  - VLC, Skype and **iChat**
    - Free video chat software