Design Process

Models of the Engineering Design Process
Engineering

Definition
“... Scientists discover the world that exists; Engineers create the world that never was ...”

Theodore Von Karman, Aerospace engineer
“... Scientists dream about doing great things. Engineers do them....”

James A. Michener, Novelist
“... No profession unleashes the spirit of innovation like engineering. From research to real world applications, engineers constantly discover how to improve our lives by creating bold new solutions that connect science to life in unexpected, forward-thinking ways. Few professions turn so many ideas into so many realities. Few have such a direct and positive effect on people's everyday lives. We are counting on engineers and their imaginations to help meet the needs of the 21st century ...”

J. Sullivan
Design Process

Engineering
Videos – Design Process

The Engineering Design Process: A Taco Party
https://youtu.be/MAhpFt_mWM

Design Thinking Process
https://youtu.be/qyoZTUGzdGY

The Design Thinking Process – Cartoon
https://youtu.be/_r0VX-aU_T8
The Waterfall Model

Engineering Design Process
<table>
<thead>
<tr>
<th>Design Step</th>
<th>Action</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Problem</td>
<td>Surveys, Case Studies, Action Research</td>
<td>Explicit Problem Definition</td>
</tr>
<tr>
<td>Problem Definition</td>
<td>Surveys, Case Studies, Action Research</td>
<td>Quantitative &amp; Qualitative Requirements</td>
</tr>
<tr>
<td>Requirement Definition</td>
<td>Creative Methods, Innovation</td>
<td>Mockups / Rapid Prototyping</td>
</tr>
<tr>
<td>Design &amp; Development</td>
<td>Optimization</td>
<td>Primary / Secondary Design</td>
</tr>
<tr>
<td>Development Design Candidates</td>
<td>Machining / Rapid Prototyping</td>
<td>Artifact / Fully functional System</td>
</tr>
<tr>
<td>Select the Best Design (Solution)</td>
<td>Experiments, Case Studies / Action Research</td>
<td>Demonstrated Prototype (Basic Functionality)</td>
</tr>
<tr>
<td>Construct a Prototype</td>
<td>Experiments, Case Studies / Action Research</td>
<td>Evaluated Prototype (Meeting Requirements)</td>
</tr>
<tr>
<td>Demonstration</td>
<td>Summary of the Design Process / Lesson Learned</td>
<td>Final Report</td>
</tr>
<tr>
<td>Evaluate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reporting</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Redesign</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Trauma Pod
Fully Automated OR

Demonstration of the Waterfall Model
Engineering Design Process
<table>
<thead>
<tr>
<th>Design Step</th>
<th>Action</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Problem</td>
<td></td>
<td>Explicit Problem Definition</td>
</tr>
<tr>
<td>Problem Definition</td>
<td>Requirement Definition</td>
<td>Surveys, Case Studies, Action Research</td>
</tr>
<tr>
<td>Requirement Definition</td>
<td></td>
<td>Surveys, Case Studies, Action Research</td>
</tr>
<tr>
<td>Development Design</td>
<td>Development Design Candidates</td>
<td>Creative Methods, Innovation</td>
</tr>
<tr>
<td>Design &amp; Development</td>
<td>Select the Best Design (Solution)</td>
<td>Optimization</td>
</tr>
<tr>
<td></td>
<td>Construct a Prototype</td>
<td>Machining / Rapid Prototyping</td>
</tr>
<tr>
<td>Demonstration</td>
<td></td>
<td>Experiments, Case Studies / Action Research</td>
</tr>
<tr>
<td>Evaluate</td>
<td></td>
<td>Experiments, Case Studies / Action Research</td>
</tr>
<tr>
<td>Reporting</td>
<td></td>
<td>Summary of the Design Process / Lesson Learned</td>
</tr>
<tr>
<td>Redesign</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Design Question

How is the Operating Room (OR) evolved
The Operating Room (OR) in a military setting (Current) – Problem Definition
Functions in the Operating Room

- **Surgeons**
  - Primary Surgeon
  - Secondary Surgeon

- **Nurses**
  - Scrub Nurse
  - Circulation Nurse
Design Question

What is the vision of the Operating Room (OR) in a military setting (Future)?
Videos - Trauma Pod Videos

Trauma Pod – Vision

https://youtu.be/diEDvxiWCCA
OR of the Future - Vision

Integration of an intelligent surgical robotic system into the unmanned and automated operating room.

• Full Body Scan
• Simulation
• Surgical Robotic Arm Extended Mobility
• Surgeon Teleoperation Workstation
• Tool Changer (Scrub Nurse)
• Equipment Dispenser (Circulation Nurse)
• High-Level Control and Monitoring Intelligence Layer
• Inventory Management Software
How should the OR be arranged (Geometry)?
Videos - Trauma Pod Videos

Trauma Pod – Phase 1 – Final
https://youtu.be/Q0rcJCQESe8
How to assemble a design group?
## Systems Breakdown

<table>
<thead>
<tr>
<th>System</th>
<th>Organization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supervisory Controller System (SCS)</td>
<td>SRI/U. Texas</td>
</tr>
<tr>
<td>Virtual Emulator System (VES)</td>
<td>SRI/U. Texas</td>
</tr>
<tr>
<td>Monitoring Station System (MSS)</td>
<td>SRI</td>
</tr>
<tr>
<td>Supplies Dispensing System (SDS)</td>
<td>General Dynamics; U. Maryland; Steris; Columbia U.</td>
</tr>
<tr>
<td>Scrub Nurse System (SNS)</td>
<td>Oak Ridge; U. Washington</td>
</tr>
<tr>
<td>Tool Rack System (TRS)</td>
<td>Oak Ridge; U. Washington</td>
</tr>
<tr>
<td>Tool Autoloader System (TAS)</td>
<td>Oak Ridge; U. Washington</td>
</tr>
<tr>
<td>Surgical Robot System (SRS)</td>
<td>Intuitive Surgical</td>
</tr>
<tr>
<td>Master Console System (MCS)</td>
<td>Intuitive Surgical</td>
</tr>
<tr>
<td>User Interface System (UIS)</td>
<td>SRI/Intuitive Surgical</td>
</tr>
<tr>
<td>Peripherals System (PS)</td>
<td>Storz</td>
</tr>
<tr>
<td>Patient Registration System (PRS)</td>
<td>Integrated Medical Systems</td>
</tr>
<tr>
<td>Global Registration System (GRS)</td>
<td></td>
</tr>
<tr>
<td>Design Step</td>
<td>Action</td>
</tr>
<tr>
<td>-----------------------------</td>
<td>-------------------------------</td>
</tr>
<tr>
<td>Initial Problem</td>
<td>Surveys, Case Studies, Action Research</td>
</tr>
<tr>
<td>Requirement Definition</td>
<td>Surveys, Case Studies, Action Research</td>
</tr>
<tr>
<td>Design &amp; Development</td>
<td></td>
</tr>
<tr>
<td>Development Design Candidates</td>
<td></td>
</tr>
<tr>
<td>Select the Best Design (Solution)</td>
<td></td>
</tr>
<tr>
<td>Construct a Prototype</td>
<td></td>
</tr>
<tr>
<td>Demonstration</td>
<td></td>
</tr>
<tr>
<td>Evaluate</td>
<td></td>
</tr>
<tr>
<td>Reporting</td>
<td></td>
</tr>
<tr>
<td>Redesign</td>
<td></td>
</tr>
</tbody>
</table>
Design Question

What are the requirements for the OR of the future?
High Level Requirements
High Level Requirements

• Development of a robotic cell tele-surgical system the can perform a portion of a surgical procedure without nurses

• Demonstrate tool change and supply delivery within 10sec
Program Phases

1. Automate
2. Miniaturize
3. Mobilize

Spin-off
System Demo Desired Goal

• Demonstrate bowel resection and anastomoses

• Surgical Tasks:
  • Cutting
  • Suturing
  • Cauterizing
  • Irrigation and suction
  • Placing clamps
  • Removing tissue

• Automated Tasks:
  • Dispensing sutures and clamps
  • Changing needle holders, cautery scalpel, forceps, scissors
Trauma Pod Program
Phase 1 Demonstration

• Demonstrate placing a temporary shunt in the iliac vessel:
  • This procedure addresses non-compressible vessel injuries which are causing deaths in the field
  • Being able to perform this type procedure would save lives in the battlefield
System Demo Pipe Dreams

• Extend the workspace and field of view of surgical robot
• Demonstrate more complete surgical procedure: Remove clothing, sterilize patient, perform laparotomy, place IV’s
• Demonstrate system can be used in more than one patient without human assistance: Self cleaning and sterilization
• Add ‘intelligence’ to autonomous manipulators: More complex obstacle avoidance and path planning; learning algorithms; 3-D vision navigation
• Enhancing sensing to autonomous manipulators: Tactile and force sensing
• Demonstrate enabling miniature actuators or novel manipulators
Mid Level Requirements
System Functional Requirements

• The system shall be capable of conducting a portion of a teleoperated surgical procedure (TBD) requiring multiple supplies and surgical tools without the assistance of people in the operating environment.

• The system shall be capable of cutting and dissecting tissue, cauterizing, and suturing including tying sutures.

• The system shall be capable of handling a ONE patient without human intervention during the surgical procedure.

• (Failures in the operation of the system shall not result in a hazard for the patient safety.)

• The system shall generate a total record of the supplies and tools used and update the supply chain management system with re-supply requests.

• The architecture of the system shall be extendable to allow the miniaturization of the system to support the deployment in an appropriate military vehicle.
System Performance Requirements

• The length of an individual procedure shall be comparable to a procedure performed with human assistance: dispensing a supply will take no more than 10sec; Changing a tool will take no more than 10sec; Positioning a tool in the surgical site will take no more than 5sec from the tool change.

• The reliability of the operation shall be comparable to manual procedures: The system shall change 4 different tools with 100% accuracy and supply 10 different supplies with 100% correct supply and no collisions

• The system shall be able to operate in a surgical workspace of TBD cm\(^3\)

• (The system shall be capable of operating over a communication line with TBD bandwidth and TBD delay with minimal degradation.)
System Physical Requirements

- The system shall be operated by a single surgeon.
- (Tools in contact with the patient shall not be able to transmit more than TBD mA)
- (The system shall not generate introduce any toxic substances into the patient.)
- All the components of the system with the potential to interfere with the movement of the manipulators will have a means of being registered in a common three-dimensional coordinate system with a resolution of TBD and an accuracy of TBD one sigma in each dimension.
- (All equipment shall withstand cleaning and sterilization by commonly used methods without damage.)
- The total Trauma Pod system weight shall not exceed TBD pounds.
- The demonstration system shall be able to be installed within a military ISO container
System Layout
Design Question

How to develop hardware & software simultaneously
Functional Diagram
High-Level Architecture - Interfaces
Trauma Pod Concept Diagram
Definitions

Surgeon
Human being in control of the operation
Controls Trauma Pod UI and Surgical Robot System

Trauma Pod UI
Surgeon’s interface to all functions except Surgical Robot System (Intuitive Surgical)
Several possible options
Voice control and feedback
Touch panel with menus

Intuitive Surgical Robot System
A self-contained system that is controlled by its own user interface (i.e. a “black box”)
No external control interface available (true?)
Provides telemetry on arms and effectors

Management API
Programming interface for managing the Trauma Pod support functions
Logically separates the UI from the management software
Provides task selection, initiation, termination (“get me a scalpel”)
Provides task definition, scripting (“to get a scalpel, do need to do these things…”)

Trauma Pod Management Software
Task planning algorithms
Lists of robot actions required to carry out a task
Robot path planning and collision avoidance algorithms
Coordinates high-level movement of multiple robots
System status, exception handling, alerts, evasive action
Situation awareness: sensor monitoring, robot tracking
Context tracking: surgery timeline, current step in surgery
Object location database management

Physical API
Programming interface for controlling and tracking physical objects in the operating room
Logically separates the actual operating room hardware from the management software
Provides high-level motion control for individual robots except Surgical Robot System
Provides sensor output for tracking physical objects

Real World
A physical testbed containing all robot systems and supplies
Collectively, the supply dispenser, tool changer, sensors, and the non-UI part of the SRS
The final integration laboratory for all project participants

Virtual World
Implements the Physical API so that it appears identical to the Real World
Software programs model all robots (including Surgical Robot System) and sensors
Used by project participants during development
Management Software

Trauma Pod Management Software

Management API

Task Database

Task Planning

Robot Path Planning
Collision Avoidance

Object Location Database

Physical Situation Awareness

Physical API

Lighting & Camera Control

High-Level Motion Control

Task Complete

Evasive Action

Location Update

Location Update

Location Update

Object Locations

From Surgical Robot System

Sensor & Robot Data

System Status

Context Awareness

Exception Handling & Alerts

Surgery Context

Run Task

Create Task

Store Task

Retrieve Task

Alert

Status

Object Location Database

© All Rights Reserved
Trauma Pod
Management Software
Definitions

Task Planning
Breaks a high-level task ("get scalpel") into a set of robot objectives ("robot X move to here, robot Y does this")
Tasks can be created and defined via the Management API
Accepts tasks from
- Surgeon
- Exception Handling (safety)

Task Database
Contains pre-defined tasks
Stores and retrieves tasks as required

Path Planning & Collision Avoidance
Coordinates the movement of multiple robots according to the objectives set by Task Planning
Accounts for obstacles between robot current position and destination
Issues high-level motion control commands to each robot ("follow this set of linear segments, then follow an arc to here")

Object Location Database
Keeps track of location for each physical object in the operating room
Includes
- Fixed objects: tables, cabinet, etc
- Movable objects: supplies, tools, etc
- Robot arm, end geometry
- Many, many other things...

Context Awareness
Keeps the surgical procedure as a set of steps
Keeps track of the current step being performed

Exception Handling & Alerts
Monitors the physical location of objects
Forms judgments about the safety of the current physical configuration
Issues exceptions to Task Planning for making current physical configuration safe
Issues alerts to inform the surgeon

Physical Situation Awareness
Monitors robot movements and location
Monitors other object locations
Monitors supplies
Updates database as necessary

System Status
Provides system and surgical status to surgeon
Software Components - Layered Diagram
Low Level Requirements
Low Level Requirements

• Integrate robotic “cell”
  Collision avoidance, tool changing or dispensing  \( \text{Accuracy} = 100\% \)

• Accurate registration and positioning of instrument
  Precisely place instrument in on a phantom after tool change  \( \leq 1 \text{ mm} \)

• Design interconnect for tool changer
  Change new 7 DOF tool or dispense new supply  \( < 10 \text{ seconds} \)

• Real time data acquisition of tools/supplies
  Recognize and dispense instruments/supplies  \( \text{Accuracy} = 100\% \)
Some Open Issues

• System Level
  • What should the demo encompass as a goal?
  • Will there be a system to check for abnormal conditions besides sensors, such as camera?
  • If we use tools such as retractors that are not part of the robotic system we need to be able to track them and register them in space

• Supplies Dispenser System
  • How will the sterilization system avoid particles deposited on the supplies?
  • How will the supplies be packaged?
    o Packaged with no changes from today or packaged for automation? What penalty on cost are we prepared to take if packaged for automation?
  • How should the supplies be delivered and retrieved to/from the surgical site:
    o Through a special tool that can handle supplies
    o Through direct handling into the surgical site
    o Through a transfer zone outside the surgical area
  • Should be use MIS supplies, open surgery or both?
  • How are we going to keep track of all supplies: RF tagging, vision…
  • Is the SDS going to keep track of all the traffic of supplies and tools in the OR?
Some Open Issues

• Scrub Nurse System/ Tool Rack System/ Tool Autoloader System
  • Is the SNS arm going to be teleoperated to account for unexpected tasks, such as dropping a supply?
  • Is the tool rack going to be instrumented?
  • What are the assumptions for handling the tool rack in a sterile manner?
  • How are we going to load cautery tools that require electrical connections?
  • Shall we use retractors for open surgery?
  • How do we address the need to be able to sterilize the robotic arm end-effector and possibly bag some of it?
  • Will the end-effector be contaminated when it retrieves used supplies or tissue from the bowel? Do we need an end effector to supply and another to retrieve supplies?

• Surgical Robot System
  • Is the transfer zone inside or outside the surgical site? Are we going to need to extend the field of view and workspace of the robot?
  • How do we handle irrigation and suction?
  • Will we require a 4th arm?
# Supplies Dispensing System

## List of Supplies

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Purpose</th>
<th>Approx. Number Used per Case</th>
<th>Packaging, current practice</th>
<th>Packaging, Trauma Pod</th>
</tr>
</thead>
<tbody>
<tr>
<td>“sponge”</td>
<td>A 4x4” piece of coarse gauze, folded from several layers</td>
<td>To blot up small amounts of blood</td>
<td>1- 100</td>
<td>10 per pack</td>
<td>TBD</td>
</tr>
<tr>
<td>“lap pad”</td>
<td>A 10x10” or 18x18” single piece of absorbent material, like a towel</td>
<td>To blot up large amounts of blood. To act as a dam to hold back intestines other structures</td>
<td>1-25</td>
<td>10 per pack</td>
<td>TBD</td>
</tr>
<tr>
<td>“peanut”</td>
<td>Peanut sized ball of gauze</td>
<td>Used on an instrument to delicately blot or sweep tissue</td>
<td>1-25</td>
<td>5 per pack</td>
<td>TBD</td>
</tr>
<tr>
<td>suture</td>
<td>Integral needle and thread</td>
<td>To sew structures together. To stop larger bleeders.</td>
<td>1-hundreds</td>
<td>Single/multiple per pack</td>
<td>TBD</td>
</tr>
<tr>
<td>tie</td>
<td>Thread</td>
<td>To tie off blood vessels</td>
<td>1-hundreds</td>
<td>On a reel in a single pack. In cut lengths multiple to a pack</td>
<td>TBD</td>
</tr>
</tbody>
</table>
Supplies Dispensing System
Approach for Supplies Design

• Design all supplies with common physical interface to a Supply Handling Tool
• The Supply Handling Tool will be able to be mounted on the daVinci arm or directed by the robot to the surgical site
• The common physical interface can be part of the disposable (I.e.: Capsule that contains sutures), or a re-usable carrier that can grasp or house the supply
• The supplies can be designed in reels that make it easy to open
Supplies Dispensing System Issues

- How will the sterilization system avoid particles deposited on the supplies?
- How will the supplies be packaged?
  - Packaged with no changes from today or packaged for automation? What penalty on cost are we prepared to take if packaged for automation?
- How should the supplies be delivered and retrieved to/from the surgical site:
  - Through a special tool that can handle supplies
  - Through direct handling into the surgical site
  - Through a transfer zone outside the surgical area
- Should be use MIS supplies, open surgery or both?
- How are we going to keep track of all supplies: RF tagging, vision…
- Is the SDS going to keep track of all the traffic of supplies and tools in the OR?
Scrub Nurse System Approach

• Tool Handling:
  • Tool Autoloader System (TAS) allows a simple tool insertion task with very small external forces required
  • Tool Rack System (TRS) allows presenting the desired tool in a precise orientation for the SNS to grasp.
  • The TRS keeps track of the tool inventory
  • The Scrub Nurse System manipulator will have an end-effector that can tools

• Supply Handling:
  • Supplies are handled by a Supply Handling Tool compatible with the tool handling end-effector.
User Interface Requirements

- All Trauma Pod active systems controllable in real time from the Surgeon Master Console
- For Phase I demonstration, surgery set-up performed manually prior to operation
  - Patient positioning and registration
  - Supplies stocking
  - Robot position registration
  - (Other actions TBD)
- Allow surgeon to maintain hands and eyes on the surgical site to the maximum degree practical
- Minimum changes to the existing Intuitive Surgical surgeon direct interface physical configuration (displays, hand and foot controls)
User Interface Issues

• Will the surgeon be overloaded with control responsibilities?
• How do we provide system awareness without taking away attention from the surgical site?
• How do we make the surgeon aware of the choices without overwhelming the graphics with menus?
• How are the overlaid graphics handled with the 3-D vision?
• What are the training requirements?
TRS - Elements

• Mechanism
  • Post/Case - Non-Sterile
  • Magazine (15 Tools) - Detachable - Sterile

• Actuators
  • Main: Step Motor - Spinning Magazine
  • Secondary: Solenoid / Linear Actuator (Tool Release)

• Sensors
  • Absolute Position Sensing (Shaft Encoder)
  • Tool in the Bay - Proximity sensor
  • Micro Switches: 1. Solenoid, 2. Magazine/Case

• Communication
  • Internal: RT OS / C
  • External: TCP/IP
EE - Elements

- Mechanism
  - Tool Gripping Jaws - Sterile (Detachable from the gripper)

- Actuator
  - Electric Linear gripper

- Sensors
  - Griping Force - Single axis double beam force sensor
  - Handling Force - Three axes F/T Sensor
  - Tool in the Gripper - Proximity sensor
  - RFID

- Communication
  - ORNL incorporated with the SNS
Project Challenges

• Collaboration between autonomous and tele-operated systems
• Development of an advanced user interface that enables the surgeon to interact naturally with autonomous systems
• Automatic coordination of multiple robots in a very restricted space over a simulated patient
• Development of a system to store, manipulate and transfer sterile medical supplies that can be handled by robots
• Access tools from a compliant structure on the Surgical Robot
• Dispense tools and supplies within 10 seconds of command
• Track movement of supplies and events generating an automatic patient record
• Prove feasibility of field deployable CAT-Scan system
• Integrate subsystem developed by ten different organizations distributed around the country
Design Question

How to create a schedule?
Timetable / Scheduling / Milestones / Dependencies
Henry Gantt (1861–1919)
Designed such a chart around the years 1910–1915.
### Activity Schedule

<table>
<thead>
<tr>
<th>Activity</th>
<th>Predecessor</th>
<th>Time estimates</th>
<th>Expected time ($T_E$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Opt. ($O$)</td>
<td>Normal ($M$)</td>
</tr>
<tr>
<td>$a$</td>
<td>—</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>$b$</td>
<td>—</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>$c$</td>
<td>$a$</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>$d$</td>
<td>$a$</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>$e$</td>
<td>$b, c$</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>$f$</td>
<td>$d$</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>$g$</td>
<td>$e$</td>
<td>3</td>
<td>5</td>
</tr>
</tbody>
</table>

### Mathematical Formulas

\[
\mu(X) = \frac{a + 4b + c}{6} \\
\sigma(X) = \frac{c - a}{6}
\]
Master Plan Milestones

• 3 Months: System Definition and Specifications
• 6 Months: Detailed System Design – Start Fab
• 9 Months: Frozen Design
• 12 Month: Demo Subsystems Core Functionality; Software Emulator Ready to Interface with Subsystems
• 15 Month: Preliminary Subsystem Qualification Test
• 18 Month: Qualified Subsystems shipped to SRI
• 21 Month: Demo Integrated System Basic Functionality
• 24 Month: Run Final Demo
Master Plan Dependencies

• Month 1: Simulator CAD environment needs to be done before selecting manipulator and analyzing tasks.
• Month 1: The supplies package interface needs to be defined before the SNS end-effectors are designed.
• Month 1-3: Standards need to be in place before subs start writing code or defining the software architecture.
• Month 6-9: TAS and TRS need to be in tested and integrated before the SNS can be tested.
• Month 9-12: SNS software interface needs to be in place before SDS can finish the inventory tracking system
• Month 9-12: Obstacle avoidance and Path planning need to be in place to test SNS
• Month 12: Emulator package needs to be in place to test subsystems remotely
• Month 12: Subsystems software interfaces and communication need to be in place before they can be tested using the emulator
General Approach No. 1 - Phase 1

Fig 1 Top View of Robotic Cell

Fig 2 View from Control Room
<table>
<thead>
<tr>
<th>Design Step</th>
<th>Action</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Problem</td>
<td>Surveys, Case Studies, Action Research</td>
<td>Explicit Problem Definition</td>
</tr>
<tr>
<td>Problem Definition</td>
<td>Surveys, Case Studies, Action Research</td>
<td>Quantitative &amp; Qualitative Requirements</td>
</tr>
<tr>
<td>Requirement Definition</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Design &amp; Development</strong></td>
<td><strong>Development Design Candidates</strong></td>
<td><strong>Mockups / Rapid Prototyping</strong></td>
</tr>
<tr>
<td>Design Candidates</td>
<td>Creative Methods, Innovation</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Select the Best Design (Solution)</td>
<td>Primary / Secondary Design</td>
</tr>
<tr>
<td></td>
<td>Construct a Prototype</td>
<td>Artifact / Fully functional System</td>
</tr>
<tr>
<td>Demonstration</td>
<td></td>
<td>Demonstrated Prototype (Basic Functionality)</td>
</tr>
<tr>
<td>Evaluate</td>
<td></td>
<td>Evaluated Prototype (Meeting Requirements)</td>
</tr>
<tr>
<td>Reporting</td>
<td></td>
<td>Summary of the Design Process / Lesson Learned</td>
</tr>
<tr>
<td>Redesign</td>
<td></td>
<td>Final Report</td>
</tr>
</tbody>
</table>
Trauma Pod – Phase 1

General Approach No. 1
General Approach No. 1 - Phase 1

- Adapted existing surgical robot and scrub nurse manipulator
- Adapted Life Support system used in the field
- Designed custom System
  - Tool changer
  - Supply dispenser
- Developed software to
  - Coordinate surgical tasks
  - Coordinate interaction between surgeon and system
- Developed flexible software architecture
  - Expandable
  - Scalable
General Approach No. 1 - Phase 1

Fig 1 Top View of Robotic Cell

Fig 2 View from Control Room
Overall System Architecture
Trauma Pod – Phase 1

General Approach No. 2
General Approach No. 2 - Phase 1

• Research hypothesis
  • Typical Surgery – 2 surgeons that are equal to
    • Four arms
    • Four eyes
  • Macro / Micro approach for surgical robotics
  • The human arm as an analogy of a surgical robotic arm
    • Shoulder elbow & wrist – Gross manipulation / Positioning – C-arm
    • Fingers — Dexterous manipulation - Surgical robot
  • Distributed approach in occupying the surgical field with multiple arms
  • Surgical robotic arms attached to the OR bad

• Future implications
  • A surgical robotic arm that can serve itself (no need for surgical nurse)
  • Increasing the range of motion of each individual robotic arm
  • Avoiding arm-to-arm collisions
General Approach No. 2 - Phase 1
General Approach No. 2 - Phase 1
Tool Changer
General Approach No. 2 - Phase 1
Equipment Dispenser
Tool Rack Subsystem (TRS)

• Function – The TRS hosts 10 sterilized tools (max 14) of the surgical robotic system in a spinning magazine that presents upon request the selected tool in a given position and ordination to be picked up by the SNS.

• System Architecture – The removable magazine grasp/release and spin by actuators located in the TRS stationary base. The entire electronic and computer control is located in the base. The system computer control its action maintain its inventory and communicate this information along with the system status to the pod central control system.
End Effector Subsystem

• Function – The EE is mounted on the surgical nurse system and with it unified actuated grasping fingers can gasp both surgical tools and trays including disposable equipment and deliver them to the surgical robot and the surgical site form their hosting subsystems and back.

• System Architecture – Two pneumatic actuators are attached to a custom made bracket enable a collision free approach to the subsystems and the surgical site. A force sensor monitor forces/torques that are developed as a result of the EE interaction with the subsystems. Two cameras allow to visually monitor the content of the tray and the interaction with the subsystems.
<table>
<thead>
<tr>
<th>Design Step</th>
<th>Action</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Problem</td>
<td>Surveys, Case Studies, Action Research</td>
<td>Explicit Problem Definition</td>
</tr>
<tr>
<td>Problem Definition</td>
<td>Surveys, Case Studies, Action Research</td>
<td>Quantitative &amp; Qualitative Requirements</td>
</tr>
<tr>
<td>Requirement Definition</td>
<td>Creative Methods, Innovation</td>
<td>Mockups / Rapid Prototyping</td>
</tr>
<tr>
<td>Design &amp; Development</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Development Design Candidates</td>
<td>Surveys, Case Studies, Action Research</td>
<td></td>
</tr>
<tr>
<td>Select the Best Design (Solution)</td>
<td>Optimization</td>
<td>Primary / Secondary Design</td>
</tr>
<tr>
<td>Demonstrations</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Evaluation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reporting</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Redesign</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Design Step:**
- Initial Problem
- Problem Definition
- Requirement Definition
- Design & Development

**Action:**
- Surveys, Case Studies, Action Research
- Creative Methods, Innovation
- Optimization
- Machining / Rapid Prototyping
- Experiments, Case Studies / Action Research
- Experiments, Case Studies / Action Research
- Summary of the Design Process / Lesson Learned

**Outcome:**
- Explicit Problem Definition
- Quantitative & Qualitative Requirements
- Mockups / Rapid Prototyping
- Artifact / Fully functional System
- Demonstrated Prototype (Basic Functionality)
- Evaluated Prototype (Meeting Requirements)
- Final Report
<table>
<thead>
<tr>
<th>Design Step</th>
<th>Action</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Problem</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Problem Definition</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Requirement Definition</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Design &amp; Development</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Development Design Candidates</td>
<td>Surveys, Case Studies, Action Research</td>
<td>Explicit Problem Definition</td>
</tr>
<tr>
<td>Select the Best Design (Solution)</td>
<td>Creative Methods, Innovation</td>
<td>Quantitative &amp; Qualitative Requirements</td>
</tr>
<tr>
<td>Demonstration</td>
<td>Experiments, Case Studies / Action Research</td>
<td>Mockups / Rapid Prototyping</td>
</tr>
<tr>
<td>Evaluate</td>
<td>Experiments, Case Studies / Action Research</td>
<td>Primary / Secondary Design</td>
</tr>
<tr>
<td>Reporting</td>
<td>Summary of the Design Process / Lesson Learned</td>
<td>Artifact / Fully functional System</td>
</tr>
<tr>
<td>Redesign</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
End Effector Cameras
Surgical Nurse System

Tool Holder (x14)
Tool Rack System

End Effector
Surgical Nurse System

Base
Tool Rack System
TRS - Architecture

TCP/IP

- PC
- Controller
- Digital I/O

Outputs:
- Tool Pos.
- Abs Enc.

Inputs:
- Magazine (Tools)
- Step Motor
- Solenoid Linear Actuator
- Case/Post
- Micro Swt.
Design Question

How to Arrange the tools in the Tool Rack System (TRS)
Tool Rack System (TRS) – Preliminary Concepts
Design Question

How to Attached the tools to the Tool Rack System (TRS)
Design Question

What are the problems with the initial design the Tool Rack System (TRS)
Design Question

What are the potential solutions to the problem?
Tool Rack System (TRS) – Final Concept
How should be the Tool Rack System (TRS) actuated?
Actuators and Sensors

• Actuators
  • Magazine Spinning - DC Motor & Brake
  • Tool Grasping – DC Motor

• Sensors
  • Position sensor
    • Relative Position - Encoders
    • Absolute position – Optical Indicators
  • RFID Reader / Tag (on each tool)
• Camera – Pointing towards the tool head
Linear Actuator
Bearing Assembly (TRS)
Design Question

How to design the End Effector of the Scrub Nurse?
End Effector (EE)
EE Interfaces

- Tray
  - Surgical Site -> Patient / Tray / Surgical Robot System (SRS)
  - Supplied Dispensing Subsystem SDS -> Tray

- Tool
  - Tool Rack Subsystem (TRS) -> Tool
  - Tool Autoloder Subsystem -> Tool
Workspace Analysis

• Surgical Site & Arm Configuration
  • Distance between pivot points – 200 mm
  • Surgical Site Diameter – 146 mm (6”)
  • Nominal angle between the tools – 60 Deg
  • Distance between the pivot point and the surgical site – 150mm (half the length of the surgical tool)

• Arm workspace
  • Left/right +/-80 Deg = 160 Deg
  • Forward Backward +/-60 Deg = 120 Deg

• Tray size – 127 mm (5”) x 127 mm (5”) x 25.4 mm (1”)

V- Shaped
V- Shaped (Flipped)
V-Shaped – 90 Deg
Back to Back – Orthogonal
Scrub Nurse - End Effector
Design Question

What is the best design of the End Effector of the Scrub Nurse?
<table>
<thead>
<tr>
<th></th>
<th>V-hand</th>
<th>90 degree v-hand</th>
<th>long nose gripper</th>
<th>back-to-back</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>EE PHY 1.0</strong></td>
<td>4</td>
<td>2</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td><strong>Manufacturability</strong></td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td><strong>Stiffness</strong></td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td><strong>TAS – Tool</strong></td>
<td>See EE PHY 2.0, EE PHY 5.0, &amp; EE PHY 10.0</td>
<td>4</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td><strong>Surgical site – Tray interference</strong></td>
<td>See EE PHY 2.0, EE PHY 5.0, &amp; EE PHY 10.0</td>
<td>4</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td><strong>Tool Rack – Tool interference</strong></td>
<td>See EE PHY 2.0 &amp; EE PHY 9.0</td>
<td>2</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td><strong>Supplies dispenser – Tray interference</strong></td>
<td>See EE PHY 2.0</td>
<td>2</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td><strong>Workspace volume</strong></td>
<td>the volume occupied by all possible positions of</td>
<td>1</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td><strong>Dual-direction interference</strong></td>
<td>Problems with interference when tools are mounted in different directions</td>
<td>4</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td><strong>Switchability</strong></td>
<td>Easy with which the SNS can re-configure to switch between tools</td>
<td>3</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td><strong>SNS Workspace</strong></td>
<td>Utilizing the SNS Workspace</td>
<td>4</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td><strong>Sum</strong></td>
<td>34</td>
<td>34</td>
<td>24</td>
<td>32</td>
</tr>
</tbody>
</table>
Design Question

What should be the physical interface between the the End Effector of the Scrub Nurse and the tool / tray?
Tool / Tray – Lug
Design Question

Which Lug is the best interface between the End Effector of the Scrub Nurse and the tool / tray?
Design Question

How to unify the gripper of the End Effector (EE) such that it can grasp both the tool and the tray?
Design Question

How to avoid the fact that the tray may get stuck in the EE jaws
Design Question

How to address sterility of the EE jaws
Tool Rack System (TRS)

- Developed custom tool rack for 16 surgical tools
- Tools are presented in less than 1 sec from receipt of command
End Effector (EE) – Ver. 1
Design Question

How to change the design if the gripper doesn't grasp fast enough
End Effector (EE) – Ver. 2
Supply Dispensing System (SDS)

- Developed custom cabinet to store and de-package sterile supplies
- Supply trays are presented in less than 5 sec from receipt of command
Scrub Nurse System (SNS)

• Adapted off-the-shelf industrial robot with 7 degrees-of-freedom
• Capable of changing tools and dispensing supplies in less than 11sec
• Custom software performs path planning, collision detection and obstacle avoidance in a surgical environment
User Interface System

- Integrated speech recognition
- Developed prototype that interacts with emulator
- Gathered feedback from surgeons using the system

(2 lines available)
System message box
Machine Vision System

• Overhead system automatically counts supplies inside trays
Supervisory Controller System

- Coordinates all subsystems to execute task requested

<table>
<thead>
<tr>
<th>TYPE</th>
<th>TASK</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surgical</td>
<td>Change tool</td>
<td>Swap tool on SRS arm with new tool from TRS</td>
</tr>
<tr>
<td></td>
<td>Dispense supply</td>
<td>Provide supply to surgeon from the SDS or fast cache</td>
</tr>
<tr>
<td>Debug</td>
<td>Park all</td>
<td>Park all subsystems</td>
</tr>
<tr>
<td></td>
<td>Recover SNS</td>
<td>Recover SNS error automatically</td>
</tr>
<tr>
<td>Surgical Pre/Post Operative</td>
<td>Empty slots</td>
<td>Remove trays from slots and place in waste bin</td>
</tr>
<tr>
<td></td>
<td>Empty SRS arm</td>
<td>Remove tools from SRS and return to TRS</td>
</tr>
<tr>
<td></td>
<td>Populate slots</td>
<td>Populate supply slots with specified supply types</td>
</tr>
<tr>
<td></td>
<td>Populate SRS arm</td>
<td>Populate SRS arms with specified tools</td>
</tr>
<tr>
<td>Calibration</td>
<td>Calibrate (automatically or manually)</td>
<td>Calibrate locations of subsystem (PRS, SRS, TRS, SDS, fast cache)</td>
</tr>
</tbody>
</table>
Simulator Systems

- World model driven by sensory data in the robotic cell
- Served as development tool to analyze layout
- Used by collision detection systems during the operation
## Design Step

<table>
<thead>
<tr>
<th>Design Step</th>
<th>Action</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Problem</td>
<td>Surveys, Case Studies, Action Research</td>
<td>Explicit Problem Definition</td>
</tr>
<tr>
<td>Problem Definition</td>
<td>Surveys, Case Studies, Action Research</td>
<td>Quantitative &amp; Qualitative Requirements</td>
</tr>
<tr>
<td>Requirement Definition</td>
<td>Creative Methods, Innovation</td>
<td>Mockups / Rapid Prototyping</td>
</tr>
<tr>
<td>Design &amp; Development</td>
<td>Optimization</td>
<td>Primary / Secondary Design</td>
</tr>
<tr>
<td>Development Design Candidates</td>
<td>Machining / Rapid Prototyping</td>
<td>Artifact / Fully functional System</td>
</tr>
<tr>
<td>Select the Best Design (Solution)</td>
<td>Experiments, Case Studies / Action Research</td>
<td>Demonstrated Prototype (Basic Functionality)</td>
</tr>
<tr>
<td>Construct a Prototype</td>
<td>Experiments, Case Studies / Action Research</td>
<td>Evaluated Prototype (Meeting Requirements)</td>
</tr>
<tr>
<td>Demonstration</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Evaluate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reporting</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Redesign</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
End Effector Version

Version 1

Version 2
## End Effector Spec

<table>
<thead>
<tr>
<th>EE Version</th>
<th>1</th>
<th>2</th>
<th>Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Actuator</strong></td>
<td>Electric (Servo) Schunk PT-AP 70</td>
<td>Pneumatic Schunk RH 918</td>
<td>*</td>
</tr>
<tr>
<td><strong>Time open/close [s]</strong></td>
<td>0.63 - 0.75</td>
<td>0.4 (Stroke 60 mm) 0.28 (Stroke 42 mm)</td>
<td>0.4 Timing Analysis CTL-023-R02</td>
</tr>
<tr>
<td><strong>Stroke [mm]</strong></td>
<td>70</td>
<td>60</td>
<td>42</td>
</tr>
<tr>
<td><strong>Grasping Force [N]</strong></td>
<td>200</td>
<td>5 -100</td>
<td>15 -100</td>
</tr>
<tr>
<td><strong>Weight – Actuator [Kg]</strong></td>
<td>1.4 (2.8)</td>
<td>0.480 (0.960)</td>
<td>*</td>
</tr>
<tr>
<td><strong>Weight – V-Head [Kg]</strong></td>
<td>0.684</td>
<td>0.239</td>
<td>*</td>
</tr>
<tr>
<td><strong>Weight – Total [Kg]</strong></td>
<td>4.522</td>
<td>2.263</td>
<td>7.5 -10</td>
</tr>
</tbody>
</table>
TRS Overview
TRS Performance - TRS PER 1.0

• **Requirement** - The TRS shall be able to present any SRS tool in its rack for acquisition with a maximum of 0.7 s of receipt of command.

• **Performance** - Max – 648 +/- 8 ms
TRS Performance - TRS PER 1.0

Com. 6 - 16ms
Rot. 684 - 664ms

Low Level (Servo)
Serial

High Level
XML

700 ms
TRS Performance - TRS PER 1.0

Average Time for Presenting a Tool [ms]

6 trials – 1350 Transitions
Max – 648 +/- 8 ms

<table>
<thead>
<tr>
<th></th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>13.33</td>
<td>242.17</td>
<td>350.00</td>
<td>417.33</td>
<td>480.83</td>
<td>544.17</td>
<td>594.00</td>
<td>642.17</td>
<td>648.83</td>
<td>600.83</td>
<td>546.00</td>
<td>486.83</td>
<td>419.50</td>
<td>350.67</td>
<td>243.33</td>
</tr>
<tr>
<td>1</td>
<td>240.67</td>
<td>14.00</td>
<td>242.67</td>
<td>348.67</td>
<td>425.50</td>
<td>481.33</td>
<td>547.33</td>
<td>594.00</td>
<td>644.17</td>
<td>644.00</td>
<td>600.00</td>
<td>544.83</td>
<td>485.50</td>
<td>423.33</td>
<td>354.00</td>
</tr>
<tr>
<td>2</td>
<td>348.17</td>
<td>240.67</td>
<td>14.67</td>
<td>242.67</td>
<td>346.67</td>
<td>422.00</td>
<td>484.00</td>
<td>548.17</td>
<td>594.00</td>
<td>642.00</td>
<td>648.17</td>
<td>598.17</td>
<td>545.33</td>
<td>487.33</td>
<td>425.33</td>
</tr>
<tr>
<td>3</td>
<td>418.67</td>
<td>240.67</td>
<td>14.67</td>
<td>240.83</td>
<td>349.33</td>
<td>420.83</td>
<td>486.67</td>
<td>543.33</td>
<td>594.17</td>
<td>642.83</td>
<td>644.67</td>
<td>600.00</td>
<td>550.00</td>
<td>486.00</td>
<td>426.00</td>
</tr>
<tr>
<td>4</td>
<td>483.33</td>
<td>422.83</td>
<td>348.67</td>
<td>241.33</td>
<td>14.67</td>
<td>240.67</td>
<td>348.00</td>
<td>421.33</td>
<td>481.50</td>
<td>546.67</td>
<td>593.33</td>
<td>645.33</td>
<td>645.33</td>
<td>598.67</td>
<td>548.67</td>
</tr>
<tr>
<td>5</td>
<td>544.17</td>
<td>482.67</td>
<td>240.17</td>
<td>349.33</td>
<td>242.00</td>
<td>14.67</td>
<td>242.83</td>
<td>348.33</td>
<td>421.50</td>
<td>484.67</td>
<td>545.33</td>
<td>596.00</td>
<td>644.00</td>
<td>644.67</td>
<td>598.83</td>
</tr>
<tr>
<td>6</td>
<td>592.67</td>
<td>543.50</td>
<td>484.67</td>
<td>241.67</td>
<td>14.00</td>
<td>244.00</td>
<td>348.67</td>
<td>420.00</td>
<td>482.83</td>
<td>545.33</td>
<td>593.33</td>
<td>647.67</td>
<td>647.50</td>
<td>595.50</td>
<td>646.67</td>
</tr>
<tr>
<td>7</td>
<td>643.33</td>
<td>593.33</td>
<td>543.50</td>
<td>484.83</td>
<td>242.67</td>
<td>347.33</td>
<td>242.67</td>
<td>14.00</td>
<td>244.00</td>
<td>347.33</td>
<td>420.67</td>
<td>482.00</td>
<td>546.17</td>
<td>596.17</td>
<td>646.67</td>
</tr>
<tr>
<td>8</td>
<td>645.33</td>
<td>642.17</td>
<td>592.00</td>
<td>485.50</td>
<td>423.50</td>
<td>345.33</td>
<td>240.67</td>
<td>14.67</td>
<td>241.33</td>
<td>348.67</td>
<td>420.17</td>
<td>486.17</td>
<td>549.33</td>
<td>595.00</td>
<td>646.83</td>
</tr>
<tr>
<td>9</td>
<td>596.17</td>
<td>644.67</td>
<td>592.83</td>
<td>546.17</td>
<td>485.33</td>
<td>420.67</td>
<td>348.00</td>
<td>240.17</td>
<td>14.67</td>
<td>242.83</td>
<td>348.00</td>
<td>422.00</td>
<td>492.17</td>
<td>546.83</td>
<td>647.50</td>
</tr>
<tr>
<td>10</td>
<td>549.33</td>
<td>596.83</td>
<td>646.67</td>
<td>644.17</td>
<td>595.33</td>
<td>544.00</td>
<td>482.67</td>
<td>419.33</td>
<td>349.33</td>
<td>241.33</td>
<td>14.00</td>
<td>241.33</td>
<td>345.33</td>
<td>422.67</td>
<td>484.83</td>
</tr>
<tr>
<td>11</td>
<td>488.83</td>
<td>546.00</td>
<td>602.17</td>
<td>647.33</td>
<td>648.00</td>
<td>597.33</td>
<td>544.00</td>
<td>482.67</td>
<td>420.83</td>
<td>349.33</td>
<td>242.83</td>
<td>14.67</td>
<td>242.67</td>
<td>350.00</td>
<td>424.67</td>
</tr>
<tr>
<td>12</td>
<td>422.17</td>
<td>487.50</td>
<td>544.67</td>
<td>599.33</td>
<td>648.00</td>
<td>644.67</td>
<td>594.17</td>
<td>484.00</td>
<td>422.67</td>
<td>348.00</td>
<td>243.50</td>
<td>14.67</td>
<td>242.00</td>
<td>348.67</td>
<td>424.67</td>
</tr>
<tr>
<td>13</td>
<td>350.83</td>
<td>423.33</td>
<td>487.33</td>
<td>548.17</td>
<td>600.17</td>
<td>647.33</td>
<td>644.00</td>
<td>594.00</td>
<td>547.33</td>
<td>486.67</td>
<td>422.00</td>
<td>349.50</td>
<td>241.50</td>
<td>14.67</td>
<td>241.50</td>
</tr>
<tr>
<td>14</td>
<td>245.33</td>
<td>354.00</td>
<td>425.33</td>
<td>484.67</td>
<td>549.33</td>
<td>596.00</td>
<td>646.17</td>
<td>648.00</td>
<td>595.33</td>
<td>546.00</td>
<td>486.00</td>
<td>421.33</td>
<td>348.00</td>
<td>242.67</td>
<td>16.00</td>
</tr>
</tbody>
</table>
Carousel Profile (6 Runs, 1350 pts)

Max, Mean, Min

MAX (top layer; transparent blue)

MEAN: colored solid in between w/ yellow dots

MIN (transparent green; lower layer)
TRS Calibration
TRS Spinning
TRS Performance - TRS PER 2.0/3.0

• Requirement - The TRS shall receive / release and lock / unlock in SRS tools in 0.1 seconds (goal) with a maximum of 0.3 seconds within receipt of command.

• Performance
  • Release Tool – 0.088 s
  • Receive Tool – 0.076 s
TRS Load/Unload Tools
TRS Performance - TRS PER 4.0

• **Requirement** - The TRS shall be able to present any SRS tool in its rack for acquisition by the SNS with a position accuracy and repeatability of +/-0.65mm and orientation accuracy and repeatability of +/-0.2deg.

• **Performance** - Repeatability of +/-0.177 deg
TRS Performance - TRS PER 8.0

- **Requirement** - The TRS shall have removal forces (what the SNS/EE must overcome for tool placement or removal) of less than 1lb

- **Performance** – Releasing Force
  - Pinchers Open – 0 N
  - Pinchers Close - 12 N
    Overcoming the active passive grasping
TRS Load/Unload Tools
TRS Tool Pulling
TRS Performance - TRS FUN 12.0

• **Goal:** The TRS shall be capable of sustaining autoclave-based cleaning and sterilization with tools installed
TRS Magazine Removal
TRS Performance - TRS INT 4.0

• **Requirement** - The TRS will include an external E-Stop connection that will bring halt all motorized movements.

• **Performance** –
  • Rotation
  • Load / unload Tool
  • Idle
TRS Performance - TRS INT 4.0

Option 1

110V

Power Supply

Brake

Servo

Option 2

110V

Power Supply

Brake

Servo
TRS E-Stop
TRS Performance - TRS PER 6.0

- **Requirement** - The TRS shall incorporate passive compliance to accommodate a misalignment with the SNS end-effector of +/-4mm in any direction axes and +/- 2.8 degrees in any rotational axes, while inserting a tool or picking it from the TRS.
# Tool Misalignment

<table>
<thead>
<tr>
<th>Displacement or Rotation</th>
<th>Specified</th>
<th>Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displaced to the side</td>
<td>(\pm \Delta X)</td>
<td>2 mm</td>
</tr>
<tr>
<td>Displaced Forward</td>
<td>(+ \Delta Y)</td>
<td>2 mm</td>
</tr>
<tr>
<td>Displaced Back</td>
<td>(- \Delta Y)</td>
<td>2 mm</td>
</tr>
<tr>
<td>Displaced Down</td>
<td>(- \Delta Z)</td>
<td>2 mm</td>
</tr>
<tr>
<td>Displaced Up</td>
<td>(+ \Delta Z)</td>
<td>2 mm</td>
</tr>
<tr>
<td>Rotated Forward</td>
<td>(+ \Delta \theta_x)</td>
<td>1.4 deg</td>
</tr>
<tr>
<td>Rotated Back</td>
<td>(- \Delta \theta_x)</td>
<td>1.4 deg</td>
</tr>
<tr>
<td>Rotated Left/Right</td>
<td>(\pm \Delta \theta_y)</td>
<td>1.4 deg</td>
</tr>
<tr>
<td>Rotated Along the Shaft</td>
<td>(\pm \Delta \theta_z)</td>
<td>1.4 deg</td>
</tr>
</tbody>
</table>
TRS Tool Misalignments
TRS Tool Load - Robustness
TRS Performance - TRS FUN 7.0

• **Requirement** - The TRS shall be able to sense how many SRS tools there are, location of specific tools and whether they have been used.
TRS RFID Reading Sequence
Supply Dispensing Time – Cumulative

Supply Request Timing Data 3-15-07 to 3-27-07

- Supply Request w/ Depackage (goal = 10 sec)
- Supply Request from SC
- Supply Request from FC
Tool Change Time - Cumulative

Tool Change Timing Data 3-2-07 to 3-27-07

- Machine change time (goal = 15 sec)
- Start to tool changed (goal = 10 sec)
- Unpark (goal = 5 sec)
## High Level Requirements – Deliverable (Phase 1)

<table>
<thead>
<tr>
<th>Deliverable</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Development of a robotic cell tele-surgical system the can perform a portion</td>
<td>Demonstrated basic surgical tasks</td>
</tr>
<tr>
<td>of a surgical procedure without nurses</td>
<td></td>
</tr>
<tr>
<td>Demonstrate tool change and supply delivery within 10sec</td>
<td>Tool change 11 sec; Supply delivery 5-12 sec</td>
</tr>
<tr>
<td>Design Step</td>
<td>Action</td>
</tr>
<tr>
<td>-------------------</td>
<td>------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Initial Problem</td>
<td>Surveys, Case Studies, Action Research</td>
</tr>
<tr>
<td>Problem Definition</td>
<td>Surveys, Case Studies, Action Research</td>
</tr>
<tr>
<td>Requirement Definition</td>
<td>Surveys, Case Studies, Action Research</td>
</tr>
<tr>
<td>Design &amp; Development</td>
<td>Creative Methods, Innovation</td>
</tr>
<tr>
<td>Development Design Candidates</td>
<td>Optimization</td>
</tr>
<tr>
<td>Select the Best Design (Solution)</td>
<td>Machining / Rapid Prototyping</td>
</tr>
<tr>
<td>Construct a Prototype</td>
<td>Experiments, Case Studies / Action Research</td>
</tr>
<tr>
<td>Demonstration</td>
<td>Experiments, Case Studies / Action Research</td>
</tr>
<tr>
<td>Evaluate</td>
<td>Experiments, Case Studies / Action Research</td>
</tr>
<tr>
<td>Reporting</td>
<td>Summary of the Design Process / Lesson Learned</td>
</tr>
<tr>
<td>Redesign</td>
<td></td>
</tr>
<tr>
<td>Design Step</td>
<td>Action</td>
</tr>
<tr>
<td>---------------------</td>
<td>-----------------------------------------------</td>
</tr>
<tr>
<td>Initial Problem</td>
<td></td>
</tr>
<tr>
<td>Problem Definition</td>
<td>Surveys, Case Studies, Action Research</td>
</tr>
<tr>
<td>Requirement Definition</td>
<td>Surveys, Case Studies, Action Research</td>
</tr>
<tr>
<td>Design &amp; Development</td>
<td>Development Design Candidates</td>
</tr>
<tr>
<td></td>
<td>Select the Best Design (Solution)</td>
</tr>
<tr>
<td></td>
<td>Construct a Prototype</td>
</tr>
<tr>
<td>Demonstration</td>
<td>Creative Methods, Innovation</td>
</tr>
<tr>
<td>Evaluate</td>
<td>Optimization</td>
</tr>
<tr>
<td>Reporting</td>
<td>Machining / Rapid Prototyping</td>
</tr>
<tr>
<td>Redesign</td>
<td>Experiments, Case Studies / Action Research</td>
</tr>
<tr>
<td></td>
<td>Experiments, Case Studies / Action Research</td>
</tr>
<tr>
<td></td>
<td>Summary of the Design Process / Lesson Learned</td>
</tr>
</tbody>
</table>
The Blue Dragon
BlueDRAGON - Data
Mechanism Kinematic Optimization

• Dexterous Work Space (DWS)
  • High dexterity region defined by a right circular cone with a vertex angle of $60^\circ$
  • Contains 95% of the tool motions based on in-vivo measurements.

• Extended Dexterous Work Space (EDWS)
  • The workspace required to reach the entire abdominal cavity with MIS instruments and defined by a cone with an elliptical cross section created by two orthogonal vertex angles of $60^\circ$ and $90^\circ$. 
## Engineering Specifications - BlueDRAGON

<table>
<thead>
<tr>
<th></th>
<th>DRAGON</th>
<th>UC Berkeley</th>
<th>UC Berkeley</th>
<th>UC Berkeley</th>
<th>DeVinchi</th>
<th>Zeus</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Device</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Generation</strong></td>
<td>R1 - E (95%)</td>
<td>1</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Reference</strong></td>
<td>Measured</td>
<td>Target</td>
<td>Obtained</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Base</strong></td>
<td>Overall Geometry</td>
<td>Shaft Diameter [m]</td>
<td>0.01 - 0.015</td>
<td>0.01 - 0.015</td>
<td>0.01</td>
<td>0.005</td>
</tr>
<tr>
<td><strong>Position / Orientation</strong></td>
<td>Delta Theta x [Deg]</td>
<td>53.8047</td>
<td>+/- 60</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Delta Theta y [Deg]</td>
<td>36.3807</td>
<td>+/- 80</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Delta Theta z [Deg]</td>
<td>148.0986</td>
<td>90</td>
<td>180-270</td>
<td>720</td>
<td>+/- 180</td>
</tr>
<tr>
<td></td>
<td>R [m]</td>
<td>0.1027</td>
<td>0.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Grasping Jaw s [Deg]</td>
<td>24.0819</td>
<td>*</td>
<td>0.006</td>
<td>0.002-0.003</td>
<td>0.008 min</td>
</tr>
<tr>
<td></td>
<td>Grasping Jaw s [m]</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Delta X [m]</td>
<td>0.1026</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Delta Y [m]</td>
<td>0.0815</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Delta Z [m]</td>
<td>0.0877</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Velocity (Angular Linear)</strong></td>
<td>Wx [Rad/sec]</td>
<td>0.432</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Wy [Rad/sec]</td>
<td>0.486</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Wz [Rad/sec]</td>
<td>1.053</td>
<td>9.4 min</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>VR [m/sec]</td>
<td>0.072</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Wg [Rad/sec]</td>
<td>0.0468</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Force</strong></td>
<td>Fx [N]</td>
<td>14.7299</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fz [N]</td>
<td>184.3919</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fg [N]</td>
<td>41.6085</td>
<td>15</td>
<td>5 min</td>
<td>40 min</td>
<td></td>
</tr>
<tr>
<td><strong>Torque</strong></td>
<td>Tx [Nm]</td>
<td>2.3941</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ty [Nm]</td>
<td>1.6011</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tz [Nm]</td>
<td>0.0464</td>
<td>0.088</td>
<td>0.022</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Port Locations Analysis

- Aortal Access
- Gastrectomy
- Left and Right Adrenalectomy
- Cholesystectomy
- Nissen Fundoplication
- Liver Access
- Left Nephrectomy
- Pelvic Access
- Colon
- Small Bowel Resection
Scrub Nurse - End Effector
Publications

• [CP30] Friedman Diana, Jesse Dosher, Timothy M. Kowalewski, Jacob Rosen, Blake Hannaford, Automated Tool Handling for the Trauma pod Surgical Robot, International Conference of Robotics and Automation (ICRA 07), Rome, Italy

The Follow-ups and The Aftermath
Operation @ Home
Appendectomy Kit

Real Surgery Performed Telerobotically by Real Surgeons at Half the Price!

30% Lower Infection Rate Then Hospitals

Wired Magazine - January 2005
Trauma Pod – Phase II
Vision for Phase II
Raven IV
Automation in Surgery
The Hunter Model

Engineering Design Process
Hunter-Gatherer Model

1) never go hunting alone

2) never go home prematurely

3) bring it home

don't plan, "Let" them hunt

the next big idea as we thought

THE REALLY BIG IDEA !!!

gather transport make
design prototype dark horse prototype
Videos – The Hunter Gatherer Model

EDxConstitutionDrive 2012 - Martin Steinert - "Engineering Design: Creativity AND Analysis"

https://youtu.be/NybQMjOe9Ds