Human Machine Interfaces in Minimally Invasive Surgery

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Simulating Minimally Invasive Surgical Procedures in Virtual Environments - Modeling
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Surgery - The Big Picture

Human - Machine Interface

Surgeon

Robot (master-slave)

Haptic Device

Virtual Reality

Tool

Tissue
Interfaces in MIS

- Human hand / Tool
- Tool / Port
- Port / Abdominal Wall
- Tool Tip / Organ
In-Vivo Measurements of Soft Tissue Biomechanical Characteristics
Force Reflecting Endoscopic Grasper
FREG
FREG - One DOF Bi-Lateral Control

\[ F \]

\[ \Delta \theta \]

\[ \Delta \theta / 2 \]

\[ \Delta q \]

\[ \Delta q^2 \]
FREG - Control Algorithm

Master

Slave

Master Plant
Motor
PD Controller
+\[\Sigma\]-

Motor
PD Controller

Slave Plant
Environment

Human
FREG - Modes of Operation

<table>
<thead>
<tr>
<th>Mode</th>
<th>Master (Handle)</th>
<th>Slave (Grasper Tip)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bi - Lateral</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Automatic</td>
<td>-</td>
<td>+</td>
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</tbody>
</table>
Soft Tissue Biomechanics

Quasi Linear Viscoelasticity Theory (Fung 1993)

\[ K(\lambda, t) = G(t) \times \sigma(\lambda) \quad \text{Relaxation} \]
\[ C(\lambda, t) = J(t) \times \lambda(\sigma) \quad \text{Creep} \]

- \( K(\lambda, t) \) – Relaxation Function
- \( \sigma(\lambda) \) – Elastic Response
- \( G(t) \) – Reduced Relaxation Function
- \( C(\lambda, t) \) – Relaxation Function
- \( \lambda(t) \) – Elastic Response
- \( J(t) \) – Reduced Relaxation Function
- \( \lambda \) – Length Ratio
- \( t \) – Time
Soft Tissue Biomechanics

Uni axial Elastic Response (Fung 1993)

$$\sigma = \frac{F}{A} \quad \lambda = \frac{L}{L_0}$$

$$\sigma (\lambda) = \beta \left( e^{\alpha (1-\lambda)} - 1 \right)$$

$\alpha$, $\beta$ - Parameters

$\lambda$ - Compression Ratio

$\sigma$ - Uniaxial Compression Stress [Pa]

$A$ - Compression Cross Section Area [m$^2$]

$F$ - Compression Force Applied by the grasper

$L$ - Length of the Material Compressed by the Load [m]

$L_0$ - Initial Length with Zero Load [m]
FREG - Experimental Protocol
(Video Clip)
Soft Tissues & Latex Materials
Stress - Compression Ratio

Stomach
Small Bowel
Colon
Spleen
Liver
Lung
L1
L2
L3
L4
L5

Stress - T [Pa]

Length Ratio - \( \lambda \)
\[ \sigma(\lambda) = \beta \left( e^{\alpha(1-\lambda)} - 1 \right) \]
Silicone Materials
Silicone Materials - Stress - Compression Ratio

![Graph showing stress vs. length ratio for silicone materials.](image)
Subjective Experiment - Stiffness Ranking

\[ \text{MSE} = \frac{\sum_{i=1}^{n} (ER - CR)^2}{n} \]

\[
0 < \text{MSE} < \begin{cases} 
11 & \text{Inverse} \\
3.6 & \text{Random} 
\end{cases} \]

p < 0.05

<table>
<thead>
<tr>
<th>Tool Type</th>
<th>Mean Square Error</th>
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<tr>
<td>GRASPER</td>
<td>3.15</td>
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<tr>
<td>FREG</td>
<td>1.07</td>
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<tr>
<td>HAND</td>
<td>0.25</td>
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</table>
Endoscopic Tool / Abdominal Wall Interface
Endoscopic Tool / Abdominal Wall Interface

![Graph showing the relationship between torque and angle at different psi pressures.](image)
Hidden Markov Models of Minimally Invasive Surgery
Objective Evaluation of Surgical Skills
Surgery - The Hidden Language Metaphor

Operator

HMI

Tool

Target

Resident

Language

Robot / Tool

Patient

Surgeon

Language
Objectives

- Develop surgical instruments with embedded sensors capable of measuring forces/torques

- Generate a data-base of forces/torques acquired during actual operating conditions on experimental animals

- Develop models of the surgical process for objective evaluation of surgical skills
Instrumented Endoscopic Grasper
Experimental System

- **Laptop PC (A/D)**
  - **Sensor System Controller**
    - Fx, Fy, Fz, Tx, Ty, Tz
  - **Fg**
- **GUI**
- **Mixer**
- **VCR (PIP Mode)**
- **Video**

**Equipment:**
- **Grasper**
- **Endoscope**

**Markings:**
- UW
Laparoscopic Cholecystectomy
Laparoscopic Cholecystectomy
(Video Clip)
Laparoscopic Nissen Fundoplication
Laparoscopic Nissen Fundoplication (Video Clip)
Data Processing

- Force Torque
- Video
- Vector Quantization (VQ)
- Video Analysis (State)
- Hidden Markov Model (HMM)
Forces - Raw Data
Torques - Raw Data

LC - Dissection of Gallbladder Fossa - (3/4) - CR (S)
## Surgery - The Hidden Language Elements

<table>
<thead>
<tr>
<th>Human Language</th>
<th>Surgical Language</th>
<th>HMM</th>
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<tbody>
<tr>
<td>Words</td>
<td>Tool/Tissue Interaction</td>
<td>State</td>
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<tr>
<td>Pronunciation</td>
<td>Forces / Torque</td>
<td>Observation</td>
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<td>Chapter</td>
<td>Step of the Operation</td>
<td>Single Model</td>
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<tr>
<td>Book</td>
<td>Operation</td>
<td>Multiple Models</td>
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</table>
Hidden Markov Model

q1

q2

q3

O → G R B B R G R R
Hidden Markov Model

\[ A = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \]

\[ B = \begin{bmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{bmatrix} \]

\[ \Pi = \{ \pi_1, \pi_2, \pi_3 \} \]
HMM - Training Problem

Adjusting the model parameters to maximize the probability of the observation sequence

Given: \( \lambda(A, B, \pi) \)

Adjust: \( A, B, \pi \)

Maximize: \( P(O | \lambda) \)
HMM - Evaluation Problem

Computing the probability of the observation sequence given the model

Given: \( O = o_1, o_2, \ldots, o_T \)
\( \lambda(A, B, \pi) \)

Compute: \( P(O | \lambda) \)
## Tool/Tissue Interactions - Definitions

<table>
<thead>
<tr>
<th>Type</th>
<th>State Name</th>
<th>Acronym</th>
<th>Fx</th>
<th>Fy</th>
<th>Fz</th>
<th>Tx</th>
<th>Ty</th>
<th>Tz</th>
<th>Fg</th>
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Tool/Tissue Interactions
(Video Clip)
Generalized HMM of Surgery
Laparoscopic Cholecystectomy
Exposure of Cystic Duct (2/4)
Data Reduction

\[ \begin{pmatrix} F_x \\ F_y \\ F_z \\ T_x \\ T_y \\ T_z \\ F_g \end{pmatrix} \rightarrow \text{Vector Quantization} \rightarrow \text{F/T} \]
Vector Quantization (VQ) - Step 1
Vector Quantization (VQ) - Step 2
Vector Quantization (VQ) - Step 3
F/T Clusters

- \( F_{xy} \) [N]
- \( F_{z} \) [N]
- \( T_{xy} \times 10^{-2} \) [Nm]
- \( T_{z} \times 10^{-2} \) [Nm]
- \( F_{g} \) [N]

Legend:
- GR-PS-SW - 1
- GR-PS-SW - 2
- GR-PS-SW - 3
- GR-PS-SW - 4
- GR-PS-SW - 5
- GR-PS-SW - 6
- GR-PS-SW - 7
- GR-PS-SW - 8
- GR-PS-SW - 9
F/T Clusters (Code Book) - 87
Distributions of Clusters

Tissue Manipulation

LC-1

Equal 54%
Different 46%
NS 31%
ES 15%

LC-3

Equal 8%
Different 92%
NS 23%
ES 69%

LNF-4

Equal 15%
Different 85%
NS 31%
ES 54%

LNF-3

Equal 31%
Different 69%
NS 15%
ES 54%

Tissue Dissection

LC-2

Equal 15%
Different 85%
NS 31%
ES 70%

LNF-3

Equal 31%
Different 69%
NS 15%
ES 70%

Tissue Manipulation Tissue Dissection
State Analysis - Time Sharing in States

Time [s]

Expert Surgeon
Novice Surgeon

State
Markov Model - Performance Scale

\[ \lambda_{\text{Expert}} \quad P(O | \lambda_{\text{Expert}}) \quad \lambda_{\text{Novice}} \]

\[ \lambda_{\text{Novice}} \quad P(O | \lambda_{\text{Novice}}) \]

\[ O_i \quad P(O | \lambda_i) \]

ESF

NSF
HMM Classification

Novice (0,1)

\[ C^2 = \left( \frac{d((NSF_i, ESF_i), (0,1))}{d((NSF_i, ESF_i), (1,0))} \right)^2 \]

Expert (1,0)
HMM Classification
Learning Curve of Surgical Residents - Method
Learning Curve of Surgical Residents - Results

![Graph showing normalized statistical distance vs training level]

- LC-2 - 14 States HMM
- LC-3 - 14 States HMM
Conclusions

- Analyzing Minimally invasive surgery requires a synthesis between visual and haptic information.

- Differences between expert and novice surgeons can be defined in terms of:
  - Force/Torque signatures
  - State transitions
  - Time spent in each state
Application

• Visual and haptic information Combined into a Hidden Markov Model may be used as an objective criterion or an index of performance.

• Potential applications - evaluating the performance of
  – Student performing MIS
  – Master/slave robotic system for teleoperation
  – Haptic device for virtual reality simulations.
BioRobotics Lab - University of Washington

http://rcs.ee.washington.edu/brl/


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References

- **HMM -Tutorial**

- **Tool/Tissue Interaction**

- **HMM & Surgery**