Haptics QOE/ Haptic Data Compression/ Haptic Biometrics

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    - Quality of Experience
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Research Statement

“How can we quantitatively measure users’ Quality of Experience (QoE) of Virtual Reality (haptic-audio-visual) Applications?”

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Introduction

- **Haptics: refers to “Touch”**
  - Refers to the field of sensing and manipulation through touch
  - Wide spectrum of applications: medical, gaming, etc.
  - More realistic, exciting, and intuitive manipulation

- **Haptic Applications Evaluation**
  - Uses the term Quality of Experience (QoE) vs. QoS
  - Evaluate Haptic Audio-Visual Environments (HAVE)
  - Measuring QoE is a real challenge!
    - Universal definition!
    - User centric
    - Subjectivity!
Motivation

- Designers Perspective: Help designers model haptic applications using relevant parameters in mind when designing the application.

- Users Perspective: Users will be guaranteed maximum perception benefit of the application.
The Effect of Haptics on QoE

- How much do haptics add to the QoE
- How will users experience such advantages
  - Will they be overwhelmed or exhausted
- Evaluate two applications
  - Kinesthetic
  - Tactile
Results – Haptic Preference

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean</th>
<th>Standard Deviation</th>
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<td>Usefulness</td>
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<td>Intuitiveness</td>
<td>3.92</td>
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<td>Fatigue</td>
<td>2.08</td>
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<td>Haptic Vs. Mouse</td>
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<tr>
<td>Overall QoE</td>
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<td>14.03</td>
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<table>
<thead>
<tr>
<th>Parameter</th>
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</thead>
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<tr>
<td>Realism</td>
<td>4.9</td>
<td>1.55</td>
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<td>Usefulness</td>
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<td>Excitement</td>
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<td>Discomfort</td>
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<td>1.05</td>
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<td>Haptic Preference</td>
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<td>1.44</td>
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<tr>
<td>Overall QoE</td>
<td>81.0</td>
<td>15.53</td>
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</tbody>
</table>

Haptic Experience Versus Mouse

Tactile Device Preference Rating

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Results Other Parameters

- Realism related to haptic rendering - both
- Usefulness user appreciate the interface - both
- Intuitiveness/Excitement do not correlate significantly → users will get used to it eventually
- Fatigue/Discomfort → very high inverse correlation
- Conclusion very similar for both experiments!
  - Haptics increases quality

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Investigating Fatigue Based on Haptic Data

- Fatigue
  - May result from prolonged haptic use
  - Will reduce QoE
- Patterns in haptic data ??
  - Feature Extraction and Selection
    - \( V = \{ p_x, p_y, p_z, f_x, f_y, f_z, v_x, v_y, v_z, a_x, a_y, a_z, t \} \)

- Hand written signatures based on haptics
  - 15 users → 60 trials → Thousands of samples
  - It has been noticed that after few trials most users felt fatigue

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Compute Subjective Fatigue Objectively!

Energy
- Kinetic Energy (Important for Haptic movement)
- Potential Energy (Not important in this case!)

\[(V_1^2 - V_2^2) < 0 \quad \Rightarrow \quad E_{k2} > E_{k1}\]

\[(V_1^2 - V_2^2) > 0 \quad \Rightarrow \quad E_{k2} < E_{k1}\]
QoE Taxonomy

- Definition: QoE = QoS + User Experience
- Higher level organization
QoE Taxonomy (2)

- QoS
  - Synchronization, network delay....

- User Experience
  - Perception Measures
    - Ease of usage, fatigue, intuitiveness.....
  - Rendering Quality
    - Audio, video, haptic, cross modality
  - Psychological Measures
    - Stress, phobia......
  - Physiological Measures
    - Heart rate, respiration rate, brain wave.....
Mathematical Model QoE Evaluation

- QoE = $\zeta \times QoS + (1 - \zeta) \times UE$
- Where
  \[ QoS = \frac{\sum_i \eta_i S_i}{\sum_i \eta_i} \]
- and
  \[ UE = A \frac{\sum_i \alpha_i P_i}{\sum_i \alpha_i} + B \frac{\sum_j \beta_j R_j}{\sum_j \beta_j} + C \frac{\sum_k \gamma_k P h_k}{\sum_k \gamma_k} \]
Mathematical Model Assessment

- Assess the mathematical model using two Haptic User Interface (HUI) applications
  - Applications developed at the DISCOVER Lab
  - Applications are:
    - Haptic learning system
    - Haptic-enabled UML CASE tool
- Compare overall QoE computed by mathematical model with the one provided by testing subject

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Applications Testing
Fuzzy Inference System (FIS)

- Why fuzzy systems?
  - Most parameters are fuzzy!
  - A fuzzy logic system that maps the fuzzy logic inputs to a crisp fuzzy output is needed

- Proof of Concept
  - Five parameters that are relevant to HAVE game
FIS Design

- Input/Output Selection
- Membership function design
- FIS Selection
- Rule generation
- Defuzzification of output

System MamdaniFINAL: 5 inputs, 1 outputs, 27 rules
FIS Testing

- Randomly picked users for testing
  - The other users were used for building the FIS
- Results are significant with low error

<table>
<thead>
<tr>
<th></th>
<th>Media Synch</th>
<th>Fatigue</th>
<th>Rendering</th>
<th>Deg. of Immersion</th>
<th>User Satisfaction</th>
<th>Overall User Rating</th>
<th>FIS Output</th>
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<tr>
<td>U6</td>
<td>100</td>
<td>0</td>
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<td>100</td>
<td>95</td>
<td>92</td>
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</tbody>
</table>

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Conclusion

- This work focuses on various topics related to VR QoE
- Shifting paradigm for ideal user-centric design
- Lays the foundation for evaluation without the user
  - User tests are expensive
- Contributions
  - Effect of haptic influence on QoE
  - Modeling haptic fatigue in terms of energy
  - QoE detailed taxonomy
  - Formalization of QoE through two evaluation methodologies
    - Mathematical modeling
    - Fuzzy inference system
2. Haptic compression and its applications

- Compression of voluminous haptic data files generated for:
  - Haptic training (i.e. haptic playback) → e.g. Surgery applications.
  - Haptic data analysis, → e.g. Analyses of haptic data in rehabilitation applications, or haptic biometrics applications, etc…
- In networked telepresence or telementoring applications,
  - Reduce the voluminous haptic data traffic without degrading the performance. → Network-based multimedia and virtual reality applications such as haptic-supported games.
3. Intelligent Compression of Haptic Media (I-CHAM) Architecture

- The proposed I-CHAM architecture supports both lossy and lossless compression of haptic data.

![Diagram of the I-CHAM Encoder Architecture]

**Fig. 1** Intelligent Compression of Haptic Media (I-CHAM) Encoder Architecture
3.1 Haptic Data Extraction and Interpretation

• The Haptic Data Extraction and Interpretation Module has the following functions
  • Is an interface between haptic application/device dependent data contained in the haptic file, and application/device independent I-CHAM components.
  • Reads the XML configuration file which describes all the parameters in the haptic data file.
  • It Interprets the provided parameters and feeds the parameters to the appropriate modules.
    • e.g. file format, haptic data, sampling rates, compression mode, tolerable signal degradation, etc…
3.2 Haptic Prediction

- Autoregressive (AR) models are derived for the prediction of haptic movement and force.
- An AR model attempts to predict future outputs of a system based on the previous output values.
- Advantages of AR models are:
  - It is convenient in model identification.
  - It takes into account the possible prediction error.
  - Considers the acquisition error present in sensory readings.
  - A small number of the initial data is normally required in order to initiate the prediction process.
  - It is both accurate and computationally efficient.
3.2 Haptic Prediction (Cont.)

- The AR model is mathematically depicted as follows:

\[
v_d(n) = \sum_{i=1}^{m} \Phi_{m,i} v_d(n - i) + \varepsilon_d(n), \quad (1)
\]

- Where \( v_d(n) \) corresponds to a random sequence of haptic data along the axes \( \{x, y, z\} \).
- \( \Phi_{m,i}, i = 1, \ldots, m \), are the adaptive coefficients of the AR model of order \( m \).
- \( \varepsilon_d(n) \) denotes a zero-mean white Gaussian noise.
- The conditional maximum likelihood approach is used to estimate the adaptive model parameters.
3.3 Difference Thresholds Computation

- I-CHAM takes into account that possible imperceptible degradations of the haptic signal can be tolerated.
- Human haptic perception is generally analyzed using Weber’s law of Just Noticeable Differences (JND).
- In haptic force, the JND value is a function of the current force, as follows, $JND(F) = \alpha_F \cdot F$.
- In haptic movement, the JND value is a function of the current positions that is limited to the resolution of the haptic device, $JND(P) = \pm \alpha_P$.

$\alpha_F$ of 5% is generally tolerated without any loss of immersiveness. $\alpha_P$ is considered to be the resolution of the haptic device in this case.
3.3 Difference Thresholds Computation (Cont.)

- The Euclidean distance between the current vector \( \mathbf{v}[n] \) and the predicted vector \( \hat{\mathbf{v}}[n] \) must be minimal, as both must lie within the spherical region of radius \( JND \).

- Haptic data is generally multidimensional, hence data along each axis can be assigned distinct Difference Thresholds (JNDs). For force data \( JND^x, JND^y, JND^z \) are derived as follows,

\[
\alpha_F \cdot |F_i| = |F_i - \hat{F}_i| \\
= \left[ (F_i^x - \hat{F}_i^x)^2_{\text{max}} + (F_i^y - \hat{F}_i^y)^2_{\text{max}} + (F_i^z - \hat{F}_i^z)^2_{\text{max}} \right]^{1/2}, \\
= \left[ (\gamma_x \cdot JND_i)^2 + (\gamma_y \cdot JND_i)^2 + (\gamma_z \cdot JND_i)^2 \right]^{1/2}, \\
= \left[ (JND_i^x)^2 + (JND_i^y)^2 + (JND_i^z)^2 \right]^{1/2}, \quad (2)
\]
Reminders!

- Human Perceived Wavelength Vision
  - Between 0.3 μm to 0.7 μm

- Human Perceived Frequency Sound
  - 16 Hz to 20 KHz

- For Haptic Sensitivity is up to 1 Khz
  - Max Sensitivity at 250 Hz
3.4 Scale Estimation

- Scale estimation is necessary to compute the scaling factors $\gamma_x, \gamma_y, \gamma_z$, shown in Equ. (2).
- These factors insure that greater difference thresholds are assigned along axes in which haptic activity is more prominent.
- To compute these factors, first, the average absolute deviation is determined to characterize the spread of the haptic data along each axis.
- Then the scaling factors are computed in a straightforward manner, as higher or lower values are assigned along axes with great or little haptic activity, respectively.
3.5 Data Representation

- Data Representation module has two main functions:
  - The prediction error (only) is encoded along each dimension → This scheme is evidently inspired from DPCM coding techniques.
  - Mapping the multidimensional data into a one dimensional vector, as follows,

\[
\begin{bmatrix}
  x_1 & y_1 & z_1 \\
  x_2 & y_2 & z_2 \\
  \vdots \\
  x_n & y_n & z_n \\
\end{bmatrix}
\rightarrow
\begin{bmatrix}
  x_1 & x_2 & \cdots & x_n & y_1 & y_2 & \cdots & y_n & z_1 & z_2 & \cdots & z_n \\
\end{bmatrix}
\]

- This mapping can significantly improve the performance of the run-length encoder.
3.6 Run-Length/Entropy Coding

- Run-length coding is used to encode *Runs* of zeros.
  - Runs of zeros are generally numerous as a every correct prediction is mapped to a zero value.
- Final step of I-CHAM is Entropy Coding
  - Currently Huffman coding is supported due to its simplicity and computational efficiency.
  - The Huffman coder is designed with a fixed tree where the code is constructed based on the statistical characteristics of the input haptic media file.
4. Experimental Results

- The experimental data consists of haptic position and force data.
- The haptic device is a PHANToM Omni (SensAble Technologies).
- The graphical display is an openGL-based haptic-enabled virtual environment developed for training novice surgeons to perform cataract eye surgeries.

Fig. 2 The haptic-enabled virtual environment
4. Experimental Results (Cont.)

- We test the algorithm for the compression of haptic files
  - Data acquisition is performed at 1000 Hz, for 30 seconds
  - A file size of 0.92 MB is generated (In this case, only position data is recorded)

- The recorded path is shown in Fig. 3.
  - The performance of the algorithm is highly dependent on the performance of the haptic prediction component.

Fig. 3 The expert’s path as well as the predicted path
4. Experimental Results (Cont.)

- Algorithm is tested for both Lossy and Lossless compression as in Table I.
- In the Lossless mode, a compression ratio of 7.3:1 is obtained, which is ~ 2.5:1 improvement over Zip.
- For Lossy compression, depending on the tolerable degradation (max possible degradation between the actual and the predicted values), great compression ratios can be achieved.
Case Study: Identifying Human Pattern with Haptics

Software: Virtual Environment

Hardware: Haptic Reachin Display

Ambient Intelligent Engine

<table>
<thead>
<tr>
<th>Trial</th>
<th>Timestamp</th>
<th>Position X</th>
<th>Position Y</th>
<th>Force X (N)</th>
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<td>0.23344</td>
<td>0.56768</td>
<td>0.00456</td>
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<td>1</td>
<td>0.0123090</td>
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<td>0.98976</td>
<td>0.03767</td>
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</table>

Results
Case Study: Identifying Human Pattern with Haptics

The Experiment

Dynamic Time Warping:

+ Nelder-Mead non-linear minimization

Methodology

Spectral analysis: Fast Fourier Transform

Unsupervised Method: K-Means

Graphic Representation

\[ MS = \sum_{c=1}^{3} \sum_{i=1}^{N} (d_{c,i}^{1} - l_{c,i}^{2}(t^{p}))^2 \]
Verifying such feasibility
Shoulder-Surfing Resistant Haptic-based Graphical Password

- Authentication: Textual passwords
  - Uses characters
  - Inexpensive to implement
  - Easy to change and revoke
  - User-friendly and ubiquitous
Textual Passwords Cntd.

- Secure passwords should be
  - Long (more than 8 characters)
  - Random (random looking and hard to guess)
- Secure passwords are hard to remember!
  - Saved to a file
  - Written down on a paper
How secure are textual passwords?

- Weak against dictionary attacks
  - Passwords are related or have little entropy
- Prone to theft and loss
  - If the password is saved to a file or on a paper
- Not resistant to shoulder surfing attacks
  - Attacker is visually aided with tools such as a camera, binocular, video recorder, etc.
Design New Auth’n Scheme

- Be as good as textual passwords
  - Easy changeability and revocation
  - User-friendly

- Do better than textual passwords
  - Dictionary attack resistant (high entropy and easy to remember)
  - Shoulder-surfing resistant
Related Work

Textual passwords

- Passphrase [J. Yan, 2001], LED combination [V. Roth et al, 2004]
- Shoulder-surfing not resistant

Graphical passwords:

- Shoulder surfing not resistant
Related Work Cntd.

- Biometric recognition schemes
  - Fingerprint, iris recognition, signature verification, face recognition, etc.
  - Changeability and revocation is not easy (impossible)
  - False Acceptance Rate (FAR) and False Rejection Rate (FRR) – user not friendly, as the user has to repeat.
Haptical/Graphical Password

- Use graphical passwords
  - Increasing the entropy and dictionary attack resistant
  - Easy to remember
- Use personal entropy
  - Not easy to forge
- Use visually hidden attributes
  - Unobservable and shoulder-surfing resistant
What Hidden Attributes?

- Binary pressure of the input device
  - Visually hidden,
    - when drawing a passgraph
  - Personal,
    - pressure varies from person to person
  - Repeatable,
    - with low FAR and FRR, as it is a binary input
Pressure-based Passgraph
Procedure

● System:
  ● Measure the user’s average pressure
    ● Possibly before every session

● User:
  ● Draw a secret on the grid
    ● Remember the order of connecting points
    ● Remember the points connected
  ● Vary pressure on purpose when drawing
    ● Remember the parts with very high pressure
Advantages

- Every two points on the grid can be connected
  - Increasing the domain of possible passgraphs
- High and low pressure (binary) can be applied when connecting the points
  - Repeatable and visually hidden
- Lines and points can be drawn over several times
  - Increasing the domain of passgraphs even more
Example

- (1) first part of the passgraph
- (2) second part of the passgraph
- Solid lines: path of the passgraph
- Bold lines: parts with high pressure (more than average)
Example Cntd.

(1,6,0), (2,6,0), (3,6,0),
(4,6,0), (4,5,0), (4,4,0),
(5,4,1), (6,4,1), (7,4,1),
(7,5,0), (7,6,0), (7,7,0),
(7,8,0),
(-1,-1,-1),
(6,6,0), (6,7,1), (6,8,1),
(-1,-1,-1).
Shoulder-surfer’s View Of Passgraph

- Find the points connected
- Find the order of the connected points
- Find the points parts drawn with high pressure
- Apply the same pressure
Implementation

Reachin Display System + PHANToM™

Please Draw Your Paragraph On The Grid

- Sign Up Here
- Sign In Here
- Practice
- QUIT
Implementation Cntd.
Implementation Modes

- **Practice mode**
  - Get to know the system and measure average pressure of each user

- **Sign-up mode**
  - Choose and draw a new passgraph

- **Sign-in mode**
  - Recall the passgraph and log in after a while (10 min to several days)
Evaluation Factors

- User-friendliness for 5x5 and 8x8
  - User compliance
    - willing to use pressure and easy to change
  - Easy to remember

- Security for 5x5 and 8x8
  - Large domain of possible passgraphs (high entropy)
  - Shoulder-surfing resistant
# Users’ Test Results

<table>
<thead>
<tr>
<th>Criterion</th>
<th>5x5 (100% yes)</th>
<th>8x8 (100% yes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure used</td>
<td>61.1</td>
<td>55.6</td>
</tr>
<tr>
<td>Easy to use</td>
<td>35.5</td>
<td>37.5</td>
</tr>
<tr>
<td>Meaningful</td>
<td>43.8</td>
<td>37.5</td>
</tr>
<tr>
<td>Long login time</td>
<td>77.8</td>
<td>83.3</td>
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<tr>
<td>Easy to Recall</td>
<td>64.7</td>
<td>58.8</td>
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<tr>
<td>Need to save</td>
<td>52.9</td>
<td>52.9</td>
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<tr>
<td>Easy to repeat</td>
<td>58.8</td>
<td>41.2</td>
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<tr>
<td>Easy to change</td>
<td>58.8</td>
<td>47.1</td>
</tr>
<tr>
<td>S-s resistance</td>
<td>52.9</td>
<td>64.7</td>
</tr>
</tbody>
</table>
Test Results

- Small grid is more comfortable to work with
  - Easier to vary the pressure
  - Easier to change passgraphs
  - Easier to recall passgraphs
  - Faster to draw passgraphs

- Small grid is less secure
  - More used meaningful passgraphs
  - Less resistant to shoulder-surfing attacks
Test Results Cntd.

- Mostly not comfortable varying the pressure, possibly because:
  - New to the system, 70% had no previous knowledge
  - Unwilling to change the normal behavior
- Few used meaningful passgraphs
- Grid size does not change users’ behavior
  - Saving the passgraphs for future use
  - Varying the pressure
  - Using the clues (numbers and blue lines) to memorize passgraphs
Security Evaluation

More secure than similar graphical passwords with the same size

- Any two points can be connected
- Used binary pressure

Four points on 5x5 is more secure than 8-character long textual passwords

- Three points on 8x8 is more secure than 8-character long textual passwords

- More secure to shoulder-surfing attacks

\[ (5^3 \times 5^3 \times 2^3)^n = 50^{3n} \]
Remarks

- Graphical passwords with binary pressure
  - More secure to dictionary attacks
  - More resilient to shoulder-surfing attacks
  - Lower FAR and FRR, more user-friendly
  - Changeable personal entropy

- Small grid is more comfortable, but less secure
Remarks Cntd.

- Use the large grid in highly sensitive areas
  - More secure
    - To dictionary attacks
    - Shoulder-surfing attacks
  - No effects on users’ behavior
    - Using the clues to memorize
    - Saving to a file or writing down
    - Varying the pressure
Benefits of new Media

● Much more powerful than conventional media.

Can be used to create very realistic, rich, and engaging learning experience.

Other Advantages?
● Disadvantages?

● It seems like science fiction, but it’s closer than we think.
Today’s Demos

- Cave Setup
- Kinect Tracking
- Falcon Haptic Interface
  - 3 DOF
  - Low Price
  - Science Concepts
- Reachin Display
  - Immersive 3D display
  - Phantom Desktop
    - 6 DOF
- Haptic Devices in general

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