Force Feedback in Virtual Assembly Scenarios: A Human Factors Evaluation

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Content

• Motivation – Virtual Environment (VE) Training for Space Application

• The Effects of Haptic Feedback in VE
  1. A Virtual Assembly User Study
  2. A Meta-Analysis

• Outlook: VE and Teleoperation in Space

• Discussion
Motivation:

VE Training for Space Applications

Canadarm 2

Input Devices onboard the ISS

VR Canadarm Training Simulator

All pictures by courtesy of the Canadian Space Agency, CSA
Motivation:
VE Training for Space Applications

VR simulator for Extra-Vehicular Activities (EVAs)
Motivation:
VE Training for Space Applications

DLR’s VE Training Simulator for On-Orbit Servicing (e.g. Repair, Maintenance)
Force Feedback is provided by DLR’s „HUG“ Interface
Human Performance in VE

Human Machine Interface

Motion Commands

Sensory Information

Virtual Environment
Human Performance in VE: Haptic Feedback

Human Machine Interface

Visual Information

Acoustic Information

Haptic Information

Motion Commands

Virtual Environment
# Force Feedback in Virtual Environments

## Haptic Feedback

<table>
<thead>
<tr>
<th>Force Feedback Systems</th>
<th>Vibrotactile Systems</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Force Feedback Systems" /></td>
<td><img src="image2" alt="Vibrotactile Systems" /></td>
</tr>
</tbody>
</table>

### Pros:
- Multidimensional, kinesthetic feedback
- Low-cost alternative
- Small, light-weight, larger workspaces

### Cons:
- Costly
- Often bulky, heavy, restricted workspaces
- Substitution of kinesthetic with tactile information
- Information density and complexity
Force Feedback in Virtual Environments
Visual Feedback

- Color changes (e.g. Cheng et al. 1996)

- Symbolic Arrows or bar graphs (e.g. Lécuyer et al. 2002)

- „Ghost“ Objects (e.g. Zachmann et al. 1999)

**Pros:**
- Low-cost alternative
- Unambiguous, directional information

**Cons:**
- Sensory substitution
- Visual clutter
- Increased workload
A Virtual Assembly User Study

To what extent are task performance, mental workload and spatial orientation negatively affected when substituting force feedback with vibrotactile or visual feedback of collisions?
## Apparatus: „HUG“

### Specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dynamic mass</td>
<td>2 x 14 kg</td>
</tr>
<tr>
<td>Peak force</td>
<td>2 x 150N</td>
</tr>
<tr>
<td>Number of DoF</td>
<td>2 x 7 revolute joints</td>
</tr>
<tr>
<td>Sensors in each joint</td>
<td>two position sensors, one torque sensor</td>
</tr>
<tr>
<td>Additional Sensors</td>
<td>2 x 6DoF FT-Sensor</td>
</tr>
<tr>
<td>Sampling rates</td>
<td>40 kHz current control, 3 kHz joint internal, 1 kHz Cartesian</td>
</tr>
</tbody>
</table>
**Apparatus: VibroTac**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vibration Segments</td>
<td>6 DC vibration motors</td>
</tr>
<tr>
<td>Wireless Communication</td>
<td>XBee Interface</td>
</tr>
<tr>
<td>Vibration Frequency</td>
<td>up to 180 Hz</td>
</tr>
</tbody>
</table>
Experimental Conditions

1. Visual Feedback

2. Vibrotactile Feedback

3. Force Feedback
Sample, Experimental Design, Procedure

Sample: N = 42 subjects (\(M_{\text{Age}} = 30.3\) yrs.)

Within-subject design (random condition order):

Procedure

- Instruction
- 3 Feedback Conditions
- Peg-in-hole: Small vs. large peg
Completion Time - Peg-in-hole

ANOVA
Feedback main effect:
\( F(2, 39) = 1.0; \text{ ns.} \)

Difficulty main effect:
\( F(1, 40) = 27.8; \quad p < .001 \)

Feedback x Difficulty interaction
\( F(2, 39) = 8.5; \quad p = .001 \)
Collision Forces - Peg-in-hole

ANOVA

Feedback main effect:
\[ F (2, 39) = 23.6; \quad p < .001 \]

Difficulty main effect:
\[ F (1, 40) = 7.8; \quad p < .001 \]

Feedback x Difficulty interaction
\[ F (2, 39) = 2.5; \quad p < .10 \]
Mental Workload

NASA-TLX weighted sum score (Hart & Staveland, 1988)

ANOVA
Main effect:
$F(2, 40) = 8.6$
$p = .001$
Spatial Orientation

“I had a good overview of the spatial configuration, even in situations with restricted view or occlusions” (1 = “fully disagree”; 7 = “fully agree”)

ANOVA
Main effect:
\[ F(2, 40) = 14.8 \]
\[ p < .001 \]
Discussion

*Visual feedback* potentially overloads the visual channel

*Vibrotactile feedback* is too difficult to distinguish

*Force feedback* is intuitive, easy to interpret, allowing a high degree of manipulation precision and spatial awareness
A Meta-Analysis: Aggregating all findings in the field

The overall performance effects when using vibrotactile vs. kinesthetic force feedback
Methods

1. Literature research
   → Identification of 128 primary studies on the effect of haptic feedback in the teleoperation domains.

2. Inclusion criteria
   Content:
   - Comparison of conditions with and without haptic feedback for the same task and system (omitting studies on haptic training)
   Methods:
   - Basic descriptives or statistics reported
   - Methodological control of time effects (e.g. counterbalancing)

→ 58 primary studies with $k = 171$ comparisons and $N = 1104$ subjects
→ 30 VE studies
Methods

3. Effect Size Calculation

- **Outcome Variables**
  1. Task success (task-dependent, e.g. collisions avoided)
  2. Task accuracy  (task-dependent, e.g. tissue damage)
  3. Average and peak forces
  4. Completion times

- **Calculation of Effect Sizes**

  Hedges’s  \( g = \frac{\bar{x}_{\text{No Haptics}} - \bar{x}_{\text{Haptics}}}{s_{\text{pooled}}} \)

- **Effect Size Classification**
  \( g > .20 = \text{small}; \ g > .50 = \text{medium}; \ g > .80 = \text{large effect} \)
Effect Size Aggregation – Force Feedback in All Setups

<table>
<thead>
<tr>
<th>Outcome Variable</th>
<th>k</th>
<th>Effect Size (g)</th>
<th>95% CI (g)</th>
<th>Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>Task Success</td>
<td>45</td>
<td>0.75***</td>
<td>0.64 – 0.85</td>
<td>200.4***</td>
</tr>
<tr>
<td>Task Accuracy</td>
<td>26</td>
<td>0.69***</td>
<td>0.53 – 0.85</td>
<td>46.4**</td>
</tr>
<tr>
<td>Detection Rates</td>
<td>5</td>
<td>0.62***</td>
<td>0.32 – 0.92</td>
<td>21.5***</td>
</tr>
<tr>
<td>Average Force</td>
<td>19</td>
<td>0.78***</td>
<td>0.60 – 0.96</td>
<td>169.2***</td>
</tr>
<tr>
<td>Peak Force</td>
<td>22</td>
<td>0.64***</td>
<td>0.46 – 0.82</td>
<td>132.9***</td>
</tr>
<tr>
<td>Completion Time</td>
<td>79</td>
<td>0.22***</td>
<td>0.13 – 0.30</td>
<td>331.0***</td>
</tr>
</tbody>
</table>

Note. **p < .01; ***p < .001

\( g > .20 = \text{small}; \quad g > .50 = \text{medium}; \quad g > .80 = \text{large effect} \)
### Effect Size Aggregation - Force Feedback in VE Setups

<table>
<thead>
<tr>
<th>Outcome Variable</th>
<th>k</th>
<th>Effect Size (g)</th>
<th>95% CI (g)</th>
<th>Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>Task Success</td>
<td>38</td>
<td><strong>0.68</strong>*</td>
<td>0.57 – 0.80</td>
<td>187.3***</td>
</tr>
<tr>
<td>Task Accuracy</td>
<td>12</td>
<td><strong>0.67</strong>*</td>
<td>0.47 – 0.87</td>
<td>19.6</td>
</tr>
<tr>
<td>Detection Rates</td>
<td>--</td>
<td>***</td>
<td>***</td>
<td>***</td>
</tr>
<tr>
<td>Average Force</td>
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</tr>
<tr>
<td>Peak Force</td>
<td>--</td>
<td>***</td>
<td>***</td>
<td>***</td>
</tr>
<tr>
<td>Completion Time</td>
<td>52</td>
<td><strong>0.18</strong>*</td>
<td>0.09 – 0.28</td>
<td>246.4***</td>
</tr>
</tbody>
</table>

Note. **p < .01; ***p < .001

$g > .20 = \text{small}; \ g > .50 = \text{medium}; \ g > .80 = \text{large effect}$
Differences between Force Feedback and Vibrotactile Substitution?
## Results – Feedback Modality Moderation

<table>
<thead>
<tr>
<th>Outcome Variable</th>
<th>$Q_b$</th>
<th>$k$</th>
<th>$g$</th>
<th>95% CI ($g$)</th>
<th>$Q$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Task Accuracy</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Force Feedback</td>
<td>34.2***</td>
<td>45</td>
<td>0.75***</td>
<td>0.64-0.85</td>
<td>200.4***</td>
</tr>
<tr>
<td>Vibrotactile Feedback</td>
<td>19</td>
<td>0.21**</td>
<td>0.07-0.36</td>
<td>33.6*</td>
<td></td>
</tr>
<tr>
<td><strong>Average Force</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Force Feedback</td>
<td>29.3***</td>
<td>19</td>
<td>0.78***</td>
<td>0.60-0.96</td>
<td>169.2***</td>
</tr>
<tr>
<td>Vibrotactile Feedback</td>
<td>13</td>
<td>-0.13</td>
<td>-0.41-0.15</td>
<td>105.3***</td>
<td></td>
</tr>
<tr>
<td><strong>Peak Force</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Force Feedback</td>
<td>0.1</td>
<td>22</td>
<td>0.64***</td>
<td>0.46-0.82</td>
<td>132.9***</td>
</tr>
<tr>
<td>Vibrotactile Feedback</td>
<td>5</td>
<td>0.60***</td>
<td>0.31-0.89</td>
<td>11.3**</td>
<td></td>
</tr>
<tr>
<td><strong>Completion Time</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Force Feedback</td>
<td>4.8*</td>
<td>79</td>
<td>0.22***</td>
<td>0.13-0.30</td>
<td>331***</td>
</tr>
<tr>
<td>Vibrotactile Feedback</td>
<td>18</td>
<td>0.03</td>
<td>-0.11-0.18</td>
<td>85.4***</td>
<td></td>
</tr>
</tbody>
</table>

Note. *$p < .05$; **$p < .01$; ***$p < .001$
Discussion

- **Substantial overall effects** of additional force feedback on task performance and force application

- The benefits of force feedback are **attenuated when force feedback is substituted with vibrotactile stimuli**

  ➔ Still a positive, small effect on task accuracy
  ➔ Vibrotactile information as a warning function
Outlook: VE and Teleoperation in Space

Human performance when using passive force feedback (e.g. spring stiffness) in space
Outlook: VE and Teleoperation in Space

Human Machine Interface

Motion Commands

Sensory Information

Virtual Environment
Outlook: VE and Teleoperation in Space

Main Research Question:
What are the optimal mechanical parameters (stiffness, damping, mass) of a Force Feedback Joystick under terrestrial conditions and microgravity?

Sample:
$N = 3$ cosmonauts

Pre-Mission Session  3 Mission Sessions  2 Post-Mission Session(s)
2 months before launch  2, 4, 6 weeks in space  1) 12 days after landing  2) + 6 months (after reha.)
Experimental Aiming Task

„Match static target ring as quickly as possible“
ISS Sessions November + December 2016
The Effects of Damping on Gross Motion Time

There are different optimal damping values for 1G and µG in the first weeks!

→ Moderate damping supports gross motion in µG (speed information)
The Effects of Stiffness on Fine Motion Time

There are **different optimal stiffness values for 1G and µG**!

→ Stiffness has to be reduced in µG
Summary

Degraded human performance in space:

Slower, more sluggish movement profiles when matching a static target, probably due to distorted proprioception

→ Specific mechanical properties provide crucial kinematic information, allowing for more precise and faster movements

→ There are optimal mechanical configurations for space (moderate damping, moderate stiffness)
General Discussion

• Kinesthetic Force Feedback is indispensable for teleoperation/ VE setups:
  → substantially improved accuracy, better force regulation ($gs > .60$)
  → small effects on completion time
  → lower workload, better spatial orientation

• Vibrotactile substitution still has a positive effect on task performance, but is better suited for warning/ collision detection

• Haptic assistance seems to be indispensable for maintaining high task performance in space
Thanks a lot for your attention!
References


