A SYSTEM FOR SPACE-TO-GROUND MULTI-DOF BILATERAL TELEOPERATION

João Rebelo
• Introduction
• Control architecture
• Passivity control for stability under time-delay
• Experimental setup
• Results
• Conclusions
Bilateral teleoperation

- Robots are well-suited for executing tasks in remote or inaccessible places
- Autonomous tasks executed by robots are limited
- Human decision making capabilities + robot execution
- Bilateral teleoperation systems
  - Visual feedback
  - Force feedback
• Technology demonstration for bilateral teleoperation in future exploration scenarios
• Control of robots on ground from the International Space Station as an analog scenario
• Exoskeleton devices used as master and impedance-controlled lightweight robots as slaves
- Time-delay values of 50~100ms using KONTUR-2 link (or ~800ms with KU-Forward)
Multi-dof 4-channel bilateral teleoperation
• Electrical 2- and 1-port-network system representation
• Electrical system representation

\[
\begin{align*}
&\mathbf{Z}_h & & \mathbf{Z}_m & & \mathbf{f}_{C_m}(v_m(t)) \\
&v_m(t) & & \mathbf{f}_{C_2}(f_e(t - T)) & & \mathbf{f}_{C_4}(v_s(t - T)) \\
&\mathbf{f}_{C_3}(f_h(t - T)) & & \mathbf{f}_{C_1}(v_m(t - T)) & & \mathbf{Z}_s & & v_s(t) \\
&f_e(t) & & & & Z_e
\end{align*}
\]
• Time-domain passivity control
Experimental Setup

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Experimental Setup

- Communication link characteristics
  - Mean delay: ~100ms
  - Data loss: ~20%
  - Data transmission of 44kbps @ 500Hz
  - Video transmission at 96kbps

- Practical implementation issues
  - Gravity compensation
  - Force filters due to inertial forces and noise
Experimental Setup

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Surface stiffness probing without Passivity Control
Surface stiffness probing with Passivity Control
Surface stiffness probing with Passivity Control

- Master energy in and Master energy out
- Slave energy in and Slave energy out
- PC force [N] over time [s] for X, Y, and Z axes

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Results (4)

- Stiffness measured on slave vs. stiffness rendered on master:

<table>
<thead>
<tr>
<th>Environment</th>
<th>Measured stiffness [N/m]</th>
<th>Reflected stiffness [N/m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soft</td>
<td>450</td>
<td>620</td>
</tr>
<tr>
<td>Hard</td>
<td>3700</td>
<td>1600</td>
</tr>
<tr>
<td>Rigid</td>
<td>10750</td>
<td>4500</td>
</tr>
</tbody>
</table>
Conclusions

- The system allows executing multi-dof contact tasks in bilateral teleoperation over a mobile internet connection.

- The combined force-feedback with the low bandwidth video transmission makes the system usable when only low bandwidth links are available.

- In free-air motion, additional forces of up to 10N are felt by the operator.

- Still points to be improved on the hardware, controller tuning and better understanding of human factors on task execution.