Problem

- Telesoperation of redundant robotic systems requires high cognitive workload;
- The user needs to avoid encountering the slave robot constraints [1];
- Passivity of the telesoperation system needs to be enforced.

Proposed Solution

- A task-prioritized shared-control method for remote telemanipulation of redundant robots [2];
- Haptic guidance technique to inform the user about proximity to constraints;
- Energy tanks passivity-based control to guarantee safety of the telerobotic system.

System Model

Telesoperation system: 3-DoF master haptic device and 6-DoF slave robot arm

![Diagram of the system model]

Master system

\[ M_m(q_m)\dot{q}_m + C_m(q_m, \dot{q}_m)\dot{q}_m + B_m\dot{q}_m = \tau_m + \tau_h \]

Slave system

\[ q_s = q_{s,a} + q_{s,r}, \quad q_{s,a} = \sum_{i=1}^{r} \Lambda_i P_i J_{s,i}^T \sigma_i \]

\[ q_{s,a} \rightarrow \text{autonomous tasks}, \quad q_{s,r} \rightarrow \text{user input} \]

\[ P_i = \text{i-th null-space projector} [3] \]

Cost function

\[ \mathcal{H}(q_s) = \mathcal{H}_s(q_s) + \mathcal{H}_a(q_{s,a}) \]

Coupling method

\[ q_{s,a} = \Lambda_m P_s J_{s,a}^T R_s J_m q_m \]

\[ \tau_m = -\Lambda_m J_{s,a}^T R_s J_m \mathcal{H}_a(q_{s,a}) + \mathcal{H}_a(q_{s,a}) P_s^T \nabla \mathcal{H}(q_s) \]

Passivity Analysis

Storage function and its time derivative along the system trajectories

\[ \mathcal{V}(q_m, q_s) = \frac{1}{2} q_m^T M_m q_m + \mathcal{H}(q_s) + \frac{1}{2} \sum_{i=1}^{r} \sigma_i^T \sigma_i \]

\[ \dot{\mathcal{V}} = -q_m^T B_m \dot{q}_m + q_{s,a}^T \tau_h + \sum_{i=1}^{r} \gamma_i \mathcal{V}_i \]

\[ \mathcal{H}_i(q_s) = \frac{1}{2} q_{s,i}^T H_{s,i} q_{s,i} + \mathcal{H}_a(q_{s,a}) \]

\[ \mathcal{V}_i = \bar{\mathcal{H}}_i q_{s,i}^T \bar{\mathcal{H}}_i q_{s,i} \]

\[ \tau = \mathcal{V} + \dot{\mathcal{V}} > 0 \]

Energy Tanks Passivity-based Control

The energy tank is used to implement possibly passivity violating control actions

\[ \tau_h = \sum_{i=1}^{r} \gamma_i \mathcal{V}_i \]

The system is passive w.r.t. input-output pair \((\tau_h, \dot{q}_{s,a})\) with storage function \(\mathcal{G} = \dot{\mathcal{V}} + \tau \) if

\[ \varphi = \begin{cases} 1 & \text{if } \tau < \bar{\tau} \text{ & } \gamma_i > 0 \\ 0 & \text{otherwise} \end{cases} \]

Experiments and Results

Tasks: 2 autonomous + 1 telesoperated

1. autonomous regulation of one position coordinate of the robot end-effector (1-DoF);
2. autonomous orientation regulation around a sphere centered in the object (2-DoFs) + alignment of one axis (1-DoF);
3. telesoperated user input along the remaining directions (2-DoFs), additional lowest priority task.

Experiment 1: Active behaviour of the system

![Experiment 1: Active behaviour of the system]

Experiment 2: Teleoperation

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Results:
The passivity control action dynamically stops the tasks that drive the slave robot towards the system constraints, thus preventing the user from feeling large haptic forces.

References

