Passive Task-Prioritized Shared-Control Teleoperation with Haptic Guidance

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Problem

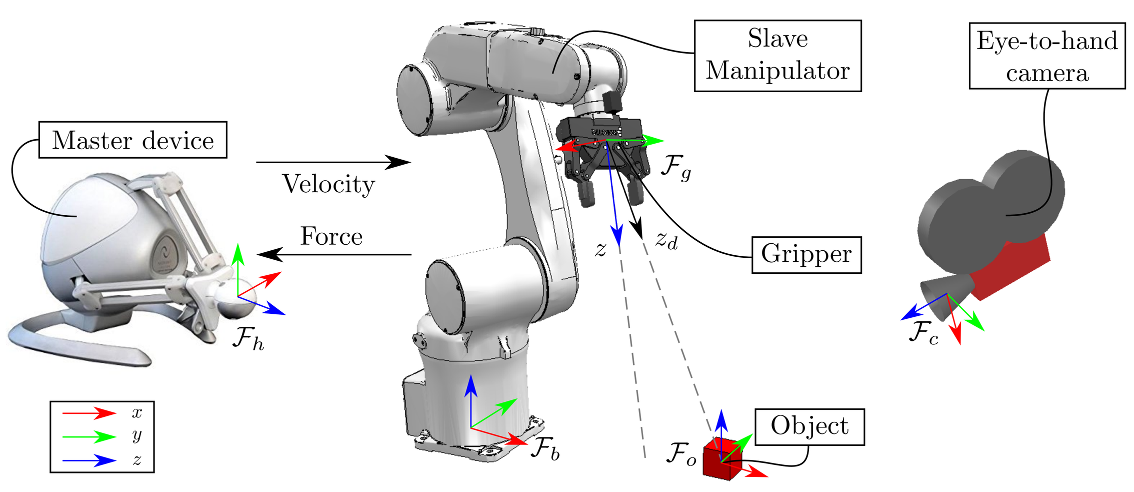
- Teleoperation of redundant robotic systems requires high cognitive workload;
- The user needs to avoid encountering the slave robot constraints [1];
- Passivity of the teleoperation system needs to be enforced.

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

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



Master system

$$\boldsymbol{M}_m(\boldsymbol{q}_m)\ddot{\boldsymbol{q}}_m + \boldsymbol{C}_m(\boldsymbol{q}_m,\dot{\boldsymbol{q}}_m)\dot{\boldsymbol{q}}_m + \boldsymbol{B}_m\dot{\boldsymbol{q}}_m = \boldsymbol{\tau}_m + \boldsymbol{\tau}_h$$

Slave system

$$\dot{\boldsymbol{q}}_s = \dot{\boldsymbol{q}}_{s,a} + \dot{\boldsymbol{q}}_{s,u}, \qquad \dot{\boldsymbol{q}}_{s,a} = \sum_{i=1}^{r} \boldsymbol{\Lambda}_i \boldsymbol{P}_{i-1}\boldsymbol{J}_{s,i}^{\dagger}\tilde{\boldsymbol{\sigma}}_i$$

$\dot{\boldsymbol{q}}_{s,a} \rightarrow$ autonomous tasks, $\dot{\boldsymbol{q}}_{s,u} \rightarrow$ user input

$\boldsymbol{P}_i$ = i-th null-space projector [3]

Cost function

$$\mathcal{H}(\boldsymbol{q}_s) = \underbrace{\mathcal{H}_j(\boldsymbol{q}_s)}_{\text{joint limits}} + \underbrace{\mathcal{H}_s(\boldsymbol{q}_s)}_{\text{singularities}}$$

Coupling method

$$\dot{\boldsymbol{q}}_{s,u} = \boldsymbol{\Lambda}_m \boldsymbol{P}_r \boldsymbol{J}_{s,u}^{\dagger}\boldsymbol{Z}_c\boldsymbol{R}_c\boldsymbol{J}_m\dot{\boldsymbol{q}}_m$$

$$\boldsymbol{\tau}_m = -\boldsymbol{\Lambda}_s\boldsymbol{J}_m^{\mathrm{T}}\boldsymbol{R}_c^{\mathrm{T}}\boldsymbol{Z}_c^{\mathrm{T}}\left(\boldsymbol{J}_{s,u}^{\dagger}\right)^{\mathrm{T}}\boldsymbol{P}_r^{\mathrm{T}}\nabla\mathcal{H}(\boldsymbol{q}_s).$$

References

[1] M. Selvaggio, F. Abi-Farraj, C. Pacchierotti, P. R. Giordano, and B. Siciliano, "Haptic-based shared-control methods for a dual-arm system," *IEEE Robot. Autom. Lett.*, vol. 3, no. 4, pp. 4249–4256, 2018.

[2] A. Dietrich, X. Wu, K. Bussmann, C. Ott, A. Albu-Schaffer, and S. Stramigioli, "Passive hierarchical impedance control via energy tanks," *IEEE Robot. Autom. Lett.*, vol. 2, no. 2, pp. 522–529, 2017.

[3] G. Antonelli, "Stability analysis for prioritized closed-loop inverse kinematic algorithms for redundant robotic systems," *IEEE Trans. Robot.*, vol. 25, no. 5, pp. 985–994, 2009.

Passivity Analysis

Storage function and its time derivative along the system trajectories

$$\mathcal{V}(\boldsymbol{q}_m,\boldsymbol{q}_s) = \frac{1}{2}\dot{\boldsymbol{q}}_m^{\mathrm{T}}\boldsymbol{M}_m\dot{\boldsymbol{q}}_m + \mathcal{H}(\boldsymbol{q}_s) + \frac{1}{2}\sum_{i=1}^{r}\tilde{\boldsymbol{\sigma}}_i^{\mathrm{T}}\tilde{\boldsymbol{\sigma}}_i$$

$$\dot{\mathcal{V}} = -\underbrace{\dot{\boldsymbol{q}}_m^{\mathrm{T}}\boldsymbol{B}_m\dot{\boldsymbol{q}}_m}_{\geq 0} + \underbrace{\dot{\boldsymbol{q}}_m^{\mathrm{T}}\boldsymbol{\tau}_h}_{\boldsymbol{y}^{\mathrm{T}}\boldsymbol{u}} + \underbrace{\left(\sum_{i=1}^{r}\boldsymbol{\Lambda}_i\boldsymbol{P}_{i-1}\boldsymbol{J}_{s,i}^{\dagger}\tilde{\boldsymbol{\sigma}}_i\right)^{\mathrm{T}}\nabla\mathcal{H}}_{=w} - \underbrace{\sum_{k=1}^{r}\tilde{\boldsymbol{\sigma}}_k\boldsymbol{J}_{s,k}\left(\sum_{i=1}^{r}\boldsymbol{\Lambda}_i\boldsymbol{P}_{i-1}\boldsymbol{J}_{s,i}^{\dagger}\tilde{\boldsymbol{\sigma}}_i\right)}_{\geq 0 \quad \text{for orthogonal/indipendent tasks}}$$

The system is not guaranteed to be passive with respect to the input-output pair ($\dot{\mathcal{V}} \leq \boldsymbol{y}^{\mathrm{T}}\boldsymbol{u}$).

Energy Tanks Passivity-based Control

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

$$\mathcal{T}(z) = \frac{1}{2}z^2, \qquad \dot{z} = \frac{\varphi}{z}\dot{\boldsymbol{q}}_m^{\mathrm{T}}\boldsymbol{B}_m\dot{\boldsymbol{q}}_m - \frac{1}{z}\sum_{i=1}^{r}\gamma_i w_i \qquad \dot{\boldsymbol{q}}_{s,a}^{\alpha} = \sum_{i=1}^{r}\alpha_i\boldsymbol{\Lambda}_i\boldsymbol{P}_{i-1}\boldsymbol{J}_{s,i}^{\dagger}\tilde{\boldsymbol{\sigma}}_i$$

α_i used to (de-)activate tasks based on the energy available in the tank ($\alpha_i \rightarrow 0$ when $\mathcal{T} \rightarrow \mathcal{T}$ and $w_i > 0$, $\alpha_i \rightarrow 1$ when $\mathcal{T} = \bar{\mathcal{T}}$). With this choice

$$\dot{\mathcal{V}} = -\dot{\boldsymbol{q}}_m^{\mathrm{T}}\boldsymbol{B}_m\dot{\boldsymbol{q}}_m + \dot{\boldsymbol{q}}_m^{\mathrm{T}}\boldsymbol{\tau}_h + \sum_{i=1}^{r}\alpha_i w_i - \sum_{k=1}^{r}\tilde{\boldsymbol{\sigma}}_k\boldsymbol{J}_{s,k}\dot{\boldsymbol{q}}_{s,a}^{\alpha}$$

$$\mathcal{G} = \mathcal{V} + \mathcal{T}, \qquad \dot{\mathcal{G}} = \dot{\mathcal{V}} + \dot{\mathcal{T}} = -(1-\varphi)\dot{\boldsymbol{q}}_m^{\mathrm{T}}\boldsymbol{B}_m\dot{\boldsymbol{q}}_m + +\dot{\boldsymbol{q}}_m^{\mathrm{T}}\boldsymbol{\tau}_h + \sum_{i=1}^{r}(\alpha_i - \gamma_i)w_i - \sum_{k=1}^{r}\tilde{\boldsymbol{\sigma}}_k\boldsymbol{J}_{s,k}\dot{\boldsymbol{q}}_{s,a}^{\alpha}$$

The system is passive w.r.t. input-output pair ($\boldsymbol{\tau}_h$, $\dot{\boldsymbol{q}}_m$) with storage function $\mathcal{G} = \mathcal{V} + \mathcal{T}$ if

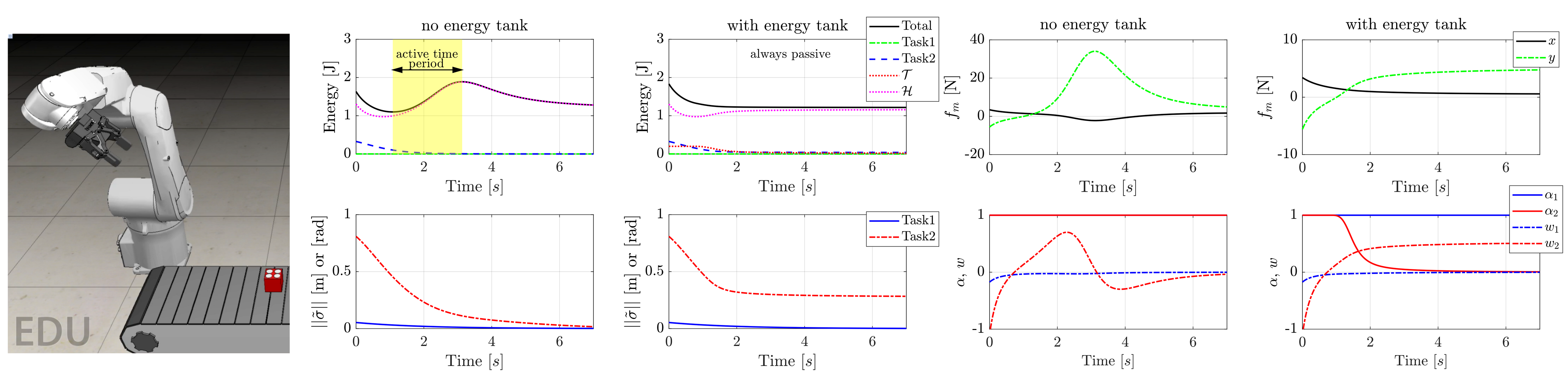
$$\varphi = \begin{cases} 1 & \text{if } \mathcal{T} < \bar{\mathcal{T}} \\ 0 & \text{otherwise} \end{cases} \qquad \gamma_i = \begin{cases} 0 & \text{if } \mathcal{T} \geq \bar{\mathcal{T}} \ \&\ w_i < 0 \\ \alpha_i & \text{otherwise} \end{cases}.$$

Experiments and Results

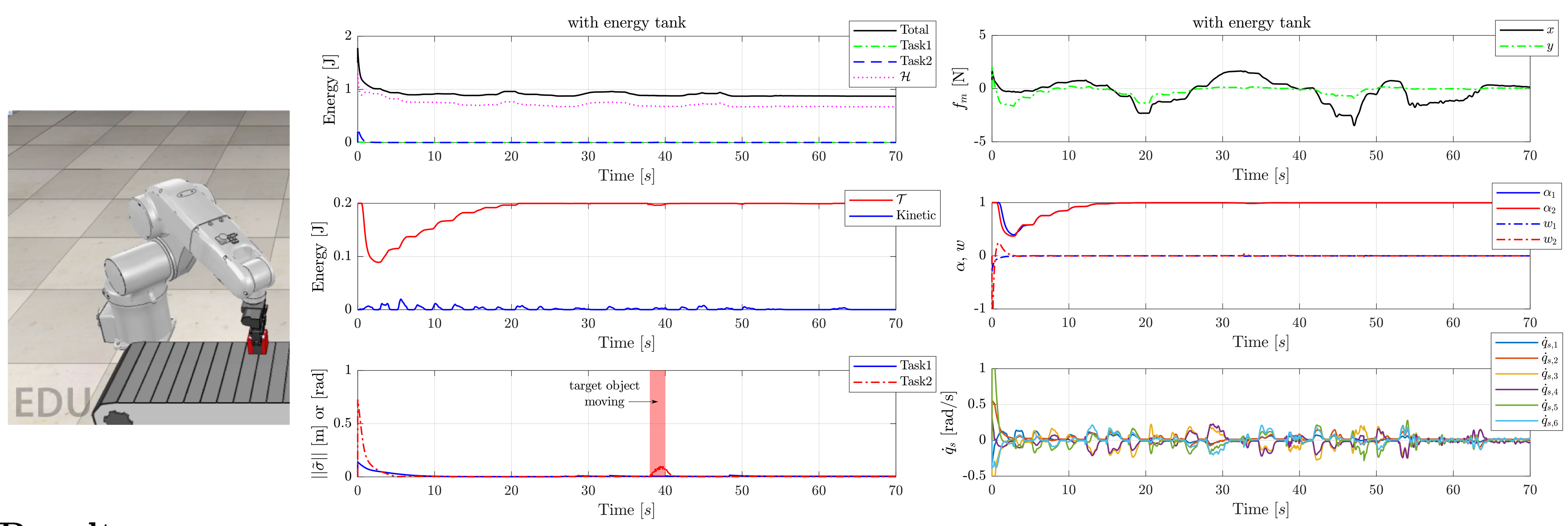
Tasks: 2 autonomous + 1 teleoperated

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. teleoperated user input along the remaining directions (2-DoFs), additional lowest priority task.

Experiment 1: Active behaviour of the system



Experiment 2: Teleoperation



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.