A Unified Framework for the Teleoperation of Surgical Robots in Constrained Workspaces

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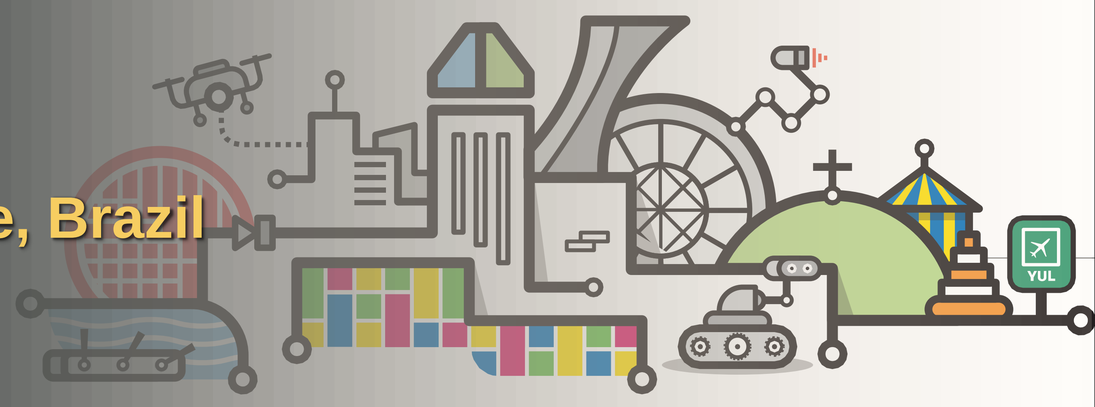
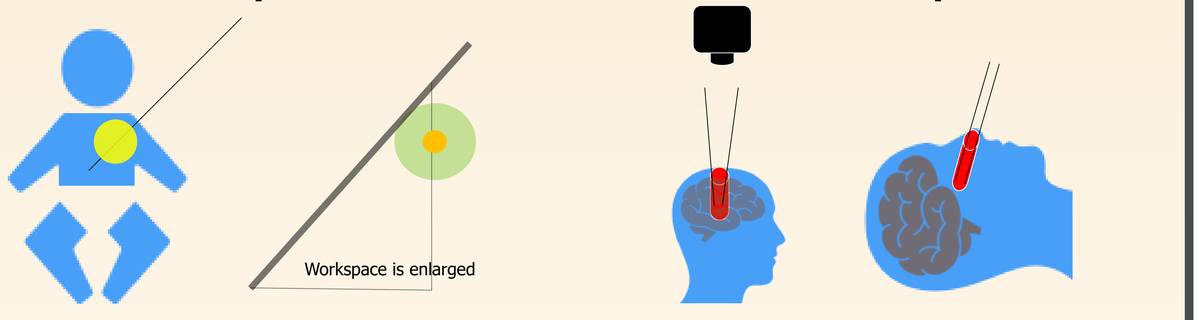


① Introduction

Teleoperation procedures in constrained workspaces require **safety** and **usability**. Moreover, the controlling framework should be **independent of robot geometry**.

Motivation: procedures in constrained workspaces

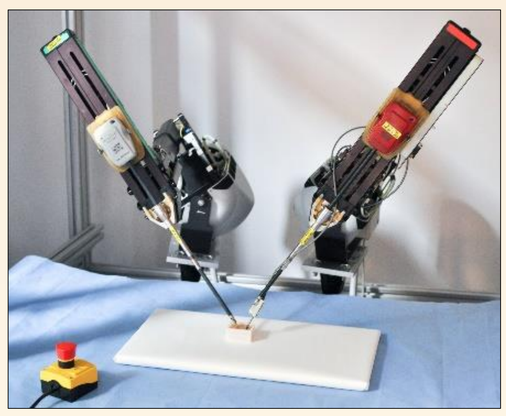


Pediatric/Infant surgery **Deep-neuro/endonasal surgery**

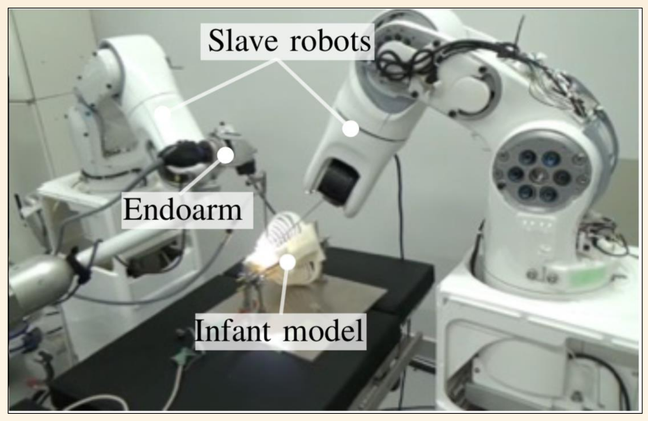
② Objective

Based on our vector-field-inequalities algorithm for virtual-fixtures, our goal is to provide **safe teleoperation** with **real-time collision avoidance**, in special for constrained workspaces in which **multiple robots interact**.

Adult laparoscopy

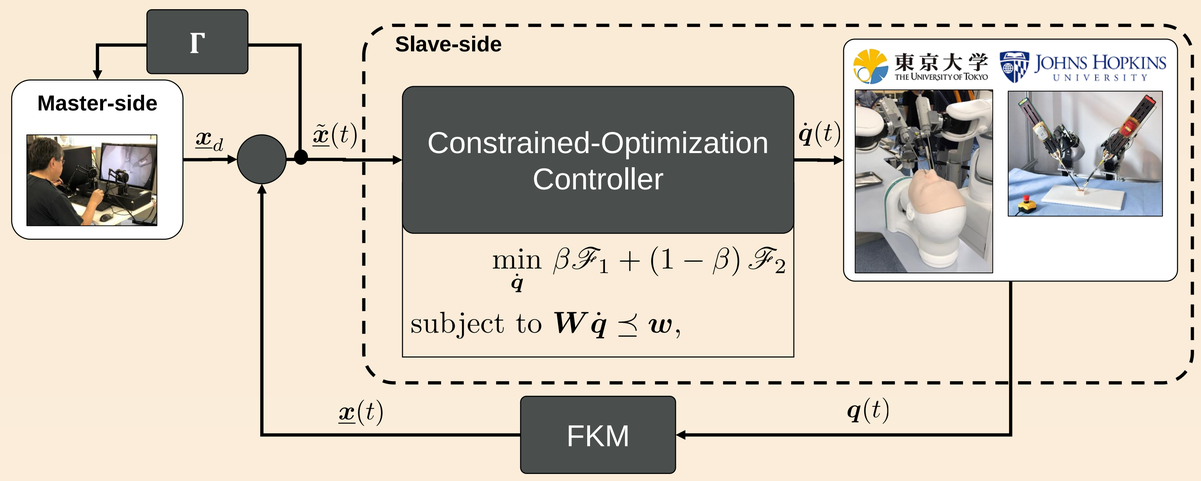


Pediatric laparoscopy



Goal: A **unified** methodology, irrespective to robot geometry

③ Proposed methodology



The proposed teleoperation approach can be divided into the master-side and the slave-side

Slave-side (Constrained optimization):

$$\min_{\dot{\boldsymbol{q}}} \beta\mathscr{F}_1 + (1-\beta)\mathscr{F}_2$$
$$\text{subject to } \boldsymbol{W}\dot{\boldsymbol{q}} \preceq \boldsymbol{w},$$

Robot 1 error term
Robot 2 error term
Robot prioritization weight
Generate virtual fixtures and joint limits

Each robot error term is given by

$$\mathscr{F}_i \triangleq \alpha \left\| \boldsymbol{J}_{i,\boldsymbol{t}}\dot{\boldsymbol{q}}_i + \eta \operatorname{vec}_3 \tilde{\boldsymbol{t}}_i \right\|_2^2 + (1-\alpha) \left\| \boldsymbol{J}_{i,\boldsymbol{r}}\dot{\boldsymbol{q}}_i + \eta \operatorname{vec}_4 \tilde{\boldsymbol{r}}_i \right\|_2^2 + \left\| \boldsymbol{\Lambda}\dot{\boldsymbol{q}}_i \right\|_2^2$$

Translation and rotation error weight
Joint velocity balancing weight
Translation error term
Rotation error term

- α Prioritizing translation is more intuitive
- $\boldsymbol{\Lambda}$ Prioritizing instrument motion is more intuitive
- β Robot prioritization can generate compliant behavior

Master-side (Cartesian impedance):

$$\boldsymbol{\Gamma}_{i,\text{master}} \triangleq -\eta_f \tilde{\boldsymbol{t}}_i^{\text{master}} - \eta_V \dot{\boldsymbol{t}}_{i,\text{master}},$$

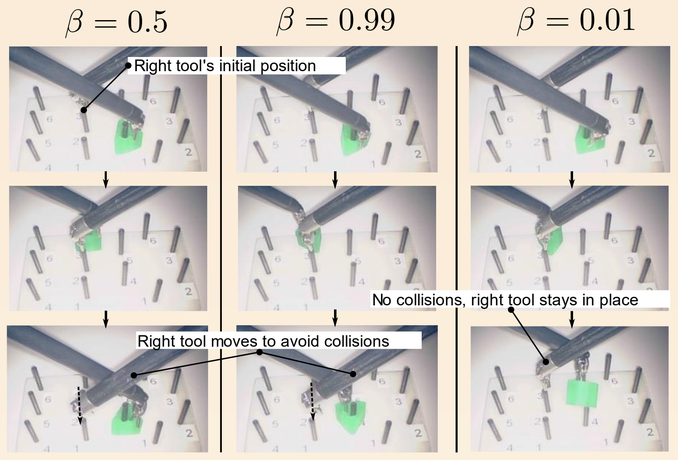
Force-feedback felt by the user
Viscosity
Force proportional to the tracking error in the slave

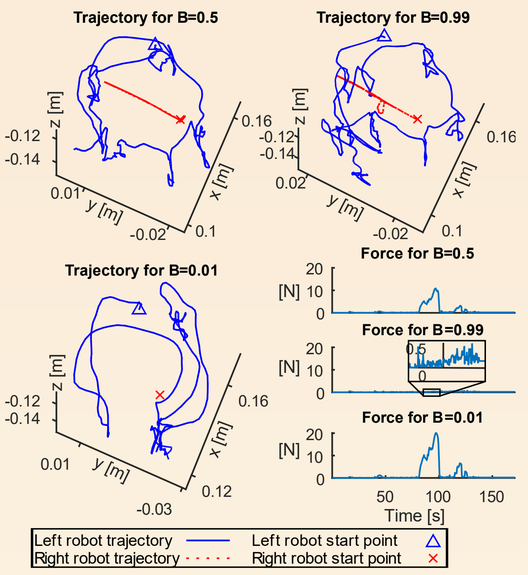
The user "feels" the direction in which the robot has difficulty moving

④ Experiments

Peg transfer using the dVRK (Adult)

Left tool teleoperated, right tool commanded to stay in place

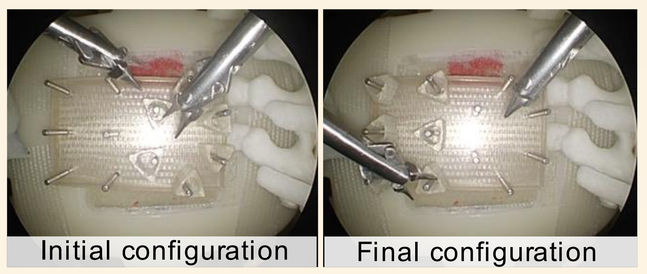


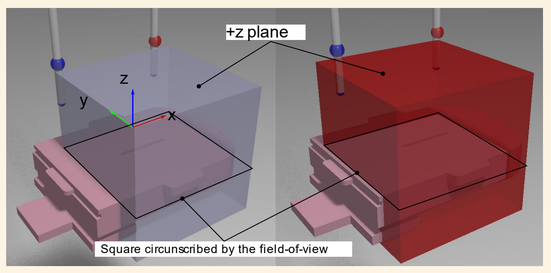


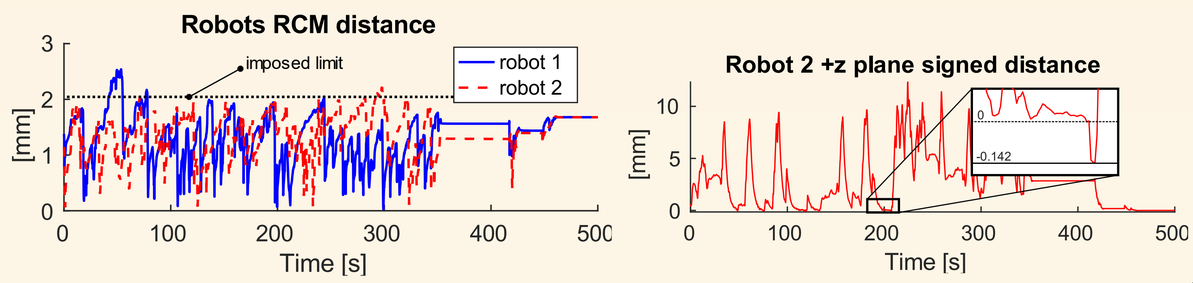
$\beta = 0.5$ shared compliance
$\beta = 0.99$ right tool compliant
$\beta = 0.01$ right tool rigid

Peg transfer using the SmartArm (Pediatric)

Robot teleoperated by a medical doctor







⑤ Conclusion

Robot prioritization and **smooth teleoperation** were achieved with the proposed methodology

This work was funded in part by the ImPACT Program of the Council for Science, Technology and Innovation (Cabinet Office, Government of Japan), in part by the JSPS KAKENHI Grant Number JP19K14935, in part by NSF grant 1637789, and in part by Johns Hopkins internal funds.

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