Torque-Bounded Task-Space Admittance Control for Redundant Manipulators

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Contribution: a Task-Space Admittance Controller

- It regulates the end-effector behavior according to predefined task-space dynamics.
- It regulates the nullspace behavior according to predefined joint-space dynamics.
- Explicit torque limits can be set on joint actuators.
- Valid even in singular configurations.
- Applicable to redundant manipulators with torque sensors.

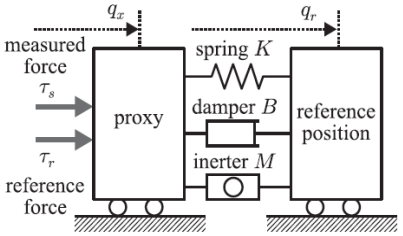
Structure: Extension of a joint-wise Torque-Bounded Admittance Control (TBAC)

[Kikuuwe 2019; IEEE-TRO]

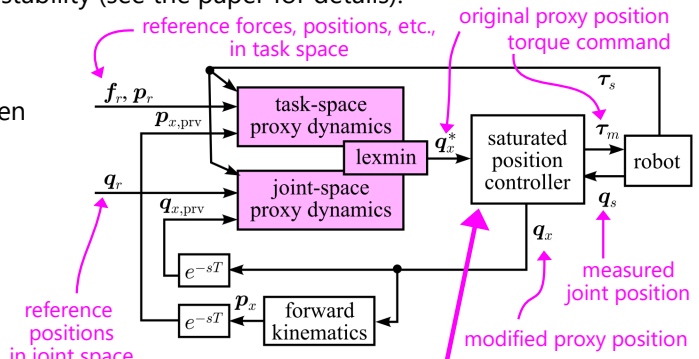
- Two "proxy" dynamics: inerter-damper-spring systems in task space ($\mathrm{SE}(3)$) and joint space ($\mathbb{R}^n$).
- They are combined via a lexicographic optimization:

$$\boldsymbol{\alpha}_x^* = \underset{\boldsymbol{\alpha}\in\mathbb{R}^n}{\mathrm{arglexmin}} \left\{ \left\| \text{torque error with respect to task-space dynamics} \right\|_{\boldsymbol{M}^{-1}}, \left\| \text{torque error with respect to joint-space dynamics} \right\|_{\boldsymbol{M}^{-1}} \right\}$$

($\boldsymbol{\alpha}_x^*$: proxy acceleration in joint space; $\boldsymbol{M}$: joint-space mass matrix)



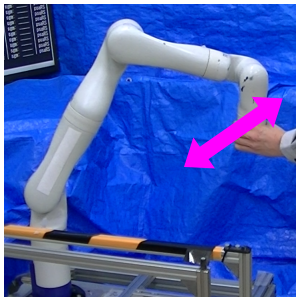
  - Task-space dynamics have priority. Joint-space dynamics take place only in the nullspace.
  - Nullspace arises from the redundancy and singular configurations.
  - Norm metric $\boldsymbol{M}^{-1}$ theoretically guarantees stability (see the paper for details).
- A new "continualized pseudoinverse" is used for lexicographic optimization.
  - Coincides with the exact pseudoinverse when the matrix is full rank.
  - Continuous even near rank-deficient cases.
  - Useful to extract nullspace components.
  - (see the paper for details).
- Robot is controlled to follow the proxy with a "Saturated Position Controller".
  - inherited from the joint-wise TBAC.
  - It modifies the proxy position to keep the torques within the preset bounds, preventing unsafe motions of the robot.



$$\begin{aligned}\tau_m^* &:= K(q_x^* - q_s) + B((q_x^* - q_{x,\mathrm{prv}})/T - u_s)\\ \tau_m &:= \mathrm{sat}(\tau^*)\\ q_x &:= (T(Kq_s + Bu_s) + Bp_{d,\mathrm{prv}} + \tau)/(KT + B)\end{aligned}$$

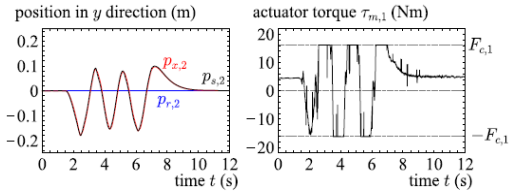
Experimental Results with a Kinova Gen3

- Behaviors under torque saturation

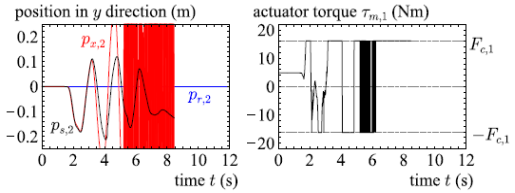


rapidly shaking the end-effector by hand

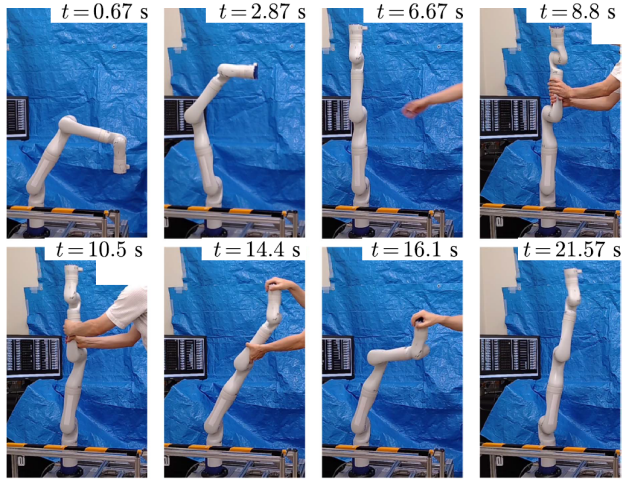
- proposed method
  - stable even under torque saturation
  - proxy and robot move together



- admittance control with PD control
  - saturation causes unsafe behavior



- Combining task-space and joint-space motions
  - End-effector follows the task-space dynamics.
  - When the robot is stretched, the links can be twisted by hand following the joint-space dynamics.



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