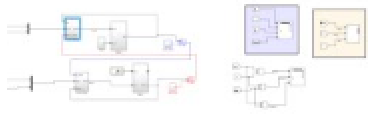
- ***Armin Attarzadeh – Tir 1403***
- ***Flexible Joint Teleopeation***

Simulation v11

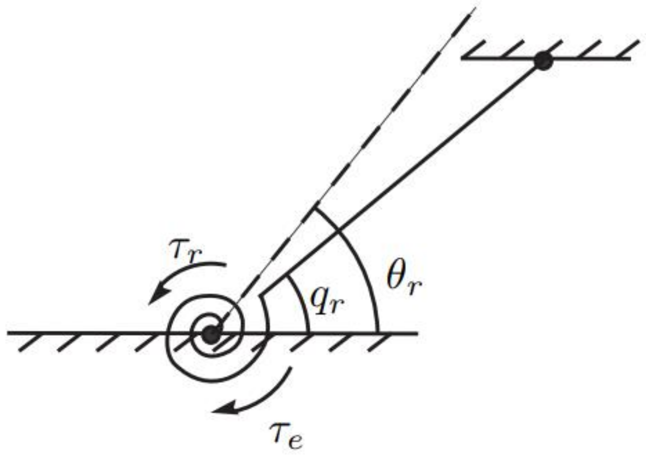


flexible_joint_v11

A Proportional Plus Damping Injection Controller for Teleoperators with Joint Flexibility and Time–Delays

Emmanuel Nuño, Ioannis Sarras, Luis Basañez and Michel Kinnaert

Non-Linear Dynamic



$$\mathbf{M}_l(\mathbf{q}_l)\ddot{\mathbf{q}}_l + \mathbf{C}_l(\mathbf{q}_l, \dot{\mathbf{q}}_l)\dot{\mathbf{q}}_l = \boldsymbol{\tau}_h - \boldsymbol{\tau}_l. \tag{1}$$

Remote: **Flexible**

$$\mathbf{M}_r(\mathbf{q}_r)\ddot{\mathbf{q}}_r + \mathbf{C}_r(\mathbf{q}_r, \dot{\mathbf{q}}_r)\dot{\mathbf{q}}_r + \mathbf{S}_r[\mathbf{q}_r - \boldsymbol{\theta}_r] = -\boldsymbol{\tau}_e \tag{2a}$$

$$\mathbf{J}_r\ddot{\boldsymbol{\theta}}_r + \mathbf{S}_r[\boldsymbol{\theta}_r - \mathbf{q}_r] = \boldsymbol{\tau}_r \tag{2b}$$

local and remote manipulators move freely in the space, $\boldsymbol{\tau}_e = \mathbf{0}.$

Non-Linear Dynamic

Local: **Rigid**

Remote: **Flexible**

$\alpha_i := l_{2_i}^2 m_{2_i} + l_{1_i}^2 (m_{1_i} + m_{2_i})$, $\beta_i := l_{1_i} l_{2_i} m_{2_i}$ and $\delta_i := l_{2_i}^2 m_{2_i}$. The inertia matrices $\mathbf{M}_i(\mathbf{q}_i) := [M_{mn}]$ are given by: $M_{11} = \alpha_i + 2\beta_i \mathrm{c}_{2_i}$, $M_{12} = M_{21} = \delta_i + \beta_i \mathrm{c}_{2_i}$ and $M_{22} = \delta_i$. c_{2_i} is the short notation for $\cos(q_{2_i})$. q_{k_i} is the position

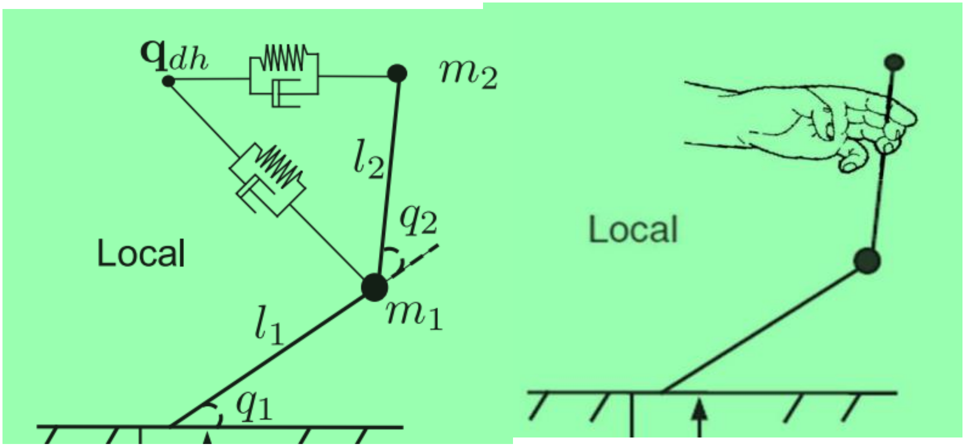
of link k of manipulator i, with $k \in \{1, 2\}$. The Coriolis and centrifugal effects are modeled by $\mathbf{C}_i(\mathbf{q}_i, \dot{\mathbf{q}}_i) = [C_{mn}]$ and are given by $C_{11} = -2\beta_i \mathrm{s}_{2_i} \dot{q}_{2_i}$, $C_{12} = -\beta_i \mathrm{s}_{2_i} \dot{q}_{2_i}$, $C_{21} = \beta_i \mathrm{s}_{2_i} \dot{q}_{1_i}$ and $C_{22} = 0$. s_{2_i} is the short notation for $\sin(q_{2_i})$. $\dot{q}_{1_i}$ and $\dot{q}_{2_i}$ are the respective revolute velocities of the two links. l_{k_i} and m_{k_i} are the respective lengths and masses of each link.

Non-Linear Dynamic

The remote motor inertia is given by $\mathbf{J}_r = 0.2\mathbf{I}$Kgm $\in \mathbb{R}^{2\times 2}$, the stiffness of the remote flexible joints is $\mathbf{S}_r = 500\mathbf{I}$Nm $\in \mathbb{R}^{2\times 2}$. The physical parameters for the manipulators are: the length of links $l_{1_i} = l_{2_i} = 0.38$m; the masses of the links are $m_{1_l} = 3.5$Kg, $m_{2_l} = 0.5$Kg, $m_{1_r} = 0.5$Kg and $m_{2_r} = 0.35$Kg. The initial conditions are $\ddot{\mathbf{q}}_i(0) = \dot{\mathbf{q}}_i(0) = \ddot{\boldsymbol{\theta}}_r(0) = \dot{\boldsymbol{\theta}}_r(0)\mathbf{0}$, $\mathbf{q}_l^\top(0) = [-1/8\pi, 1/8\pi]^\top$ and $\mathbf{q}_r^\top(0) = \boldsymbol{\theta}_r(0) = [1/5\pi, -1/2\pi]^\top$. The human operator is

Human Force Input

. The human operator is modeled as a spring-damper system with gains $K_s = 10\text{Nm}$ and $K_d = 2\text{Nms}$, respectively. Fig. 3 shows the desired trajectory for the human operator spring-damper model. The



$$\tau_h = K_h(q_d - q_l) - d\dot{q}_l$$

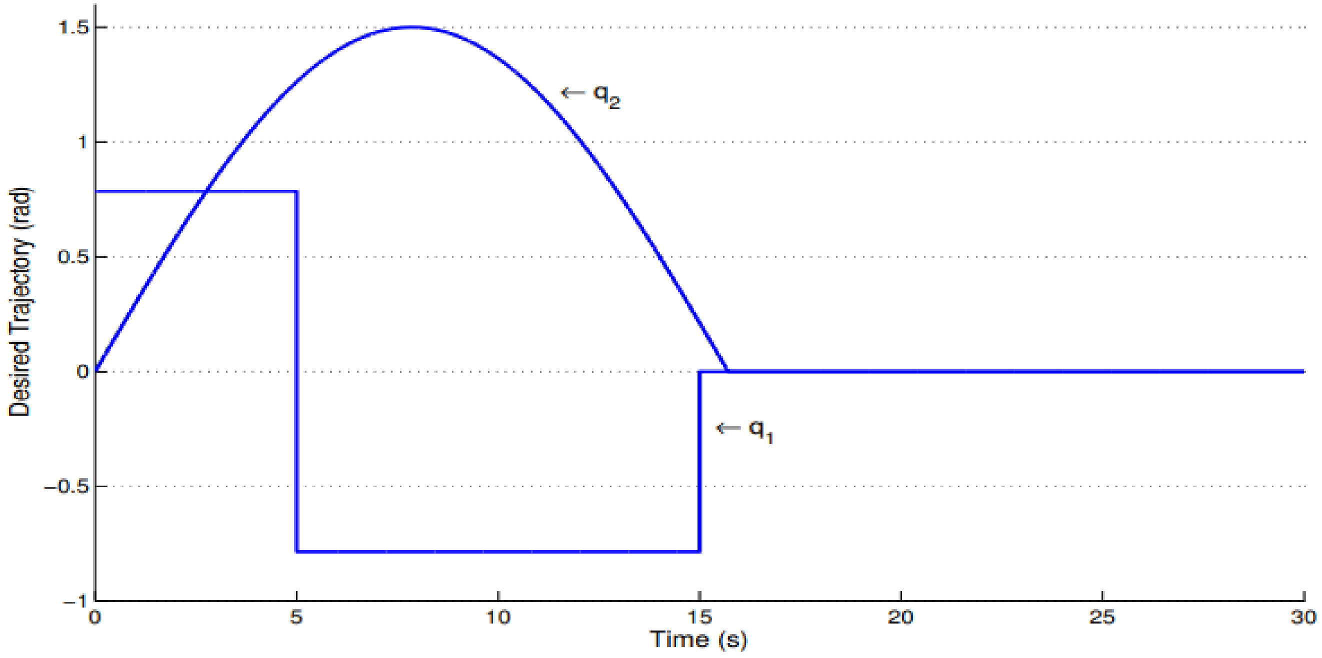
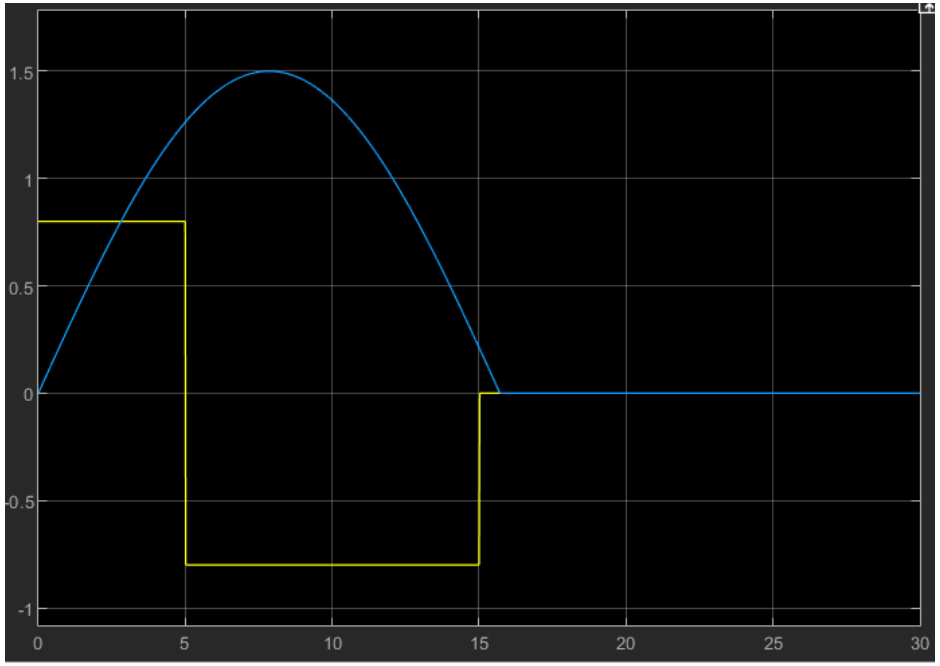


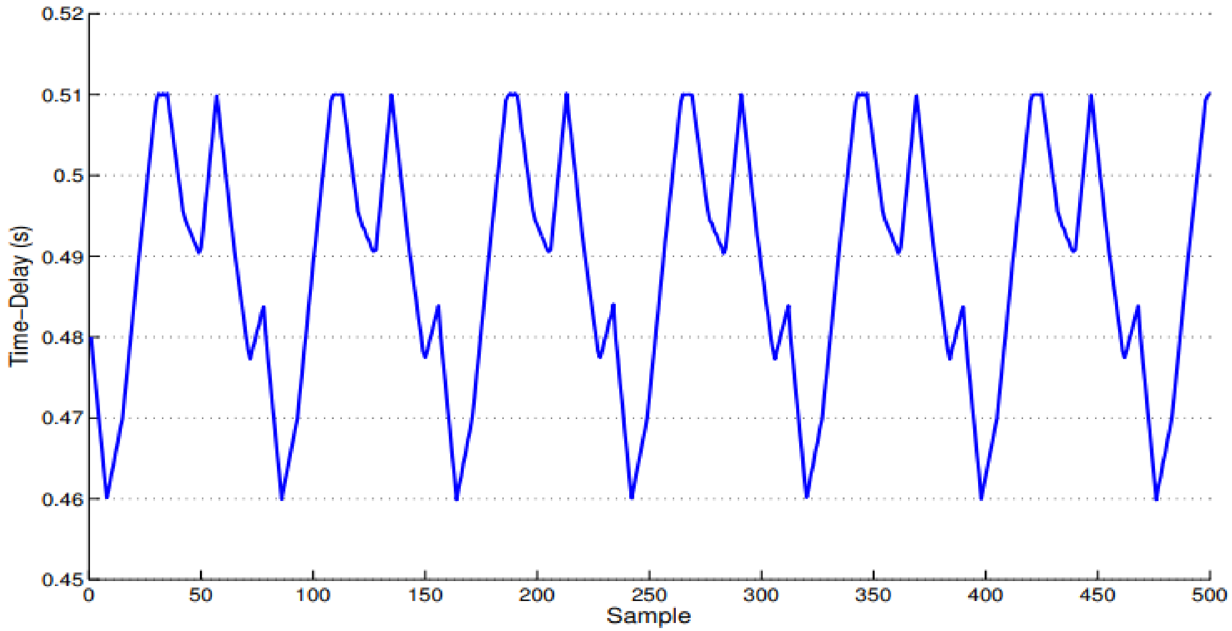
Fig. 3. Desired trajectory of the human operator.



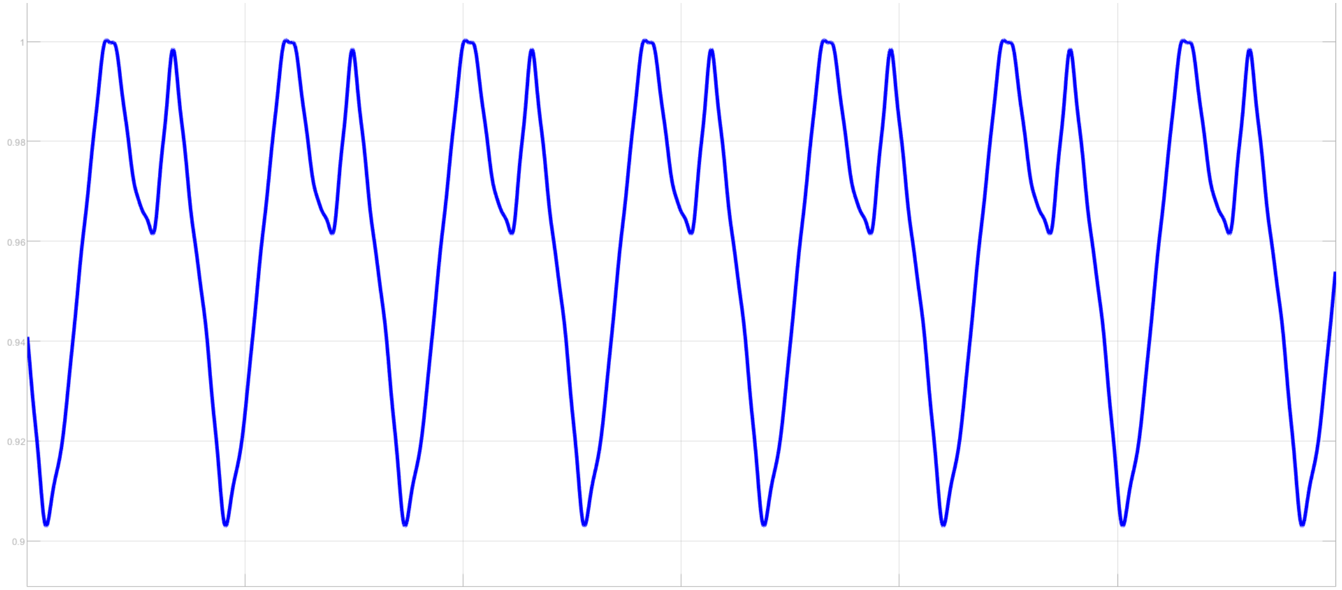
Variable Time Delay

$$0 \leq T(t) \leq {}^*T < \infty$$

$${}^*T_i = 0.55\text{s}$$



N=15 Fourier Series



Control Law : $P + d$

III. Proportional Position Error Plus Damping Injection Controller

$$\boldsymbol{\tau}_l = K_l[\mathbf{q}_l - \boldsymbol{\theta}_r(t - T_r(t))] + B_l\dot{\mathbf{q}}_l \tag{5a}$$

$$\boldsymbol{\tau}_r = K_r[\mathbf{q}_l(t - T_l(t)) - \boldsymbol{\theta}_r] - B_r\dot{\boldsymbol{\theta}}_r \tag{5b}$$

where K_i and B_i are positive constants.[2]

trajectory for the human operator spring-damper model. The local and remote controllers gains are set to $B_l = 3$Nms, $K_l = 5$Nm, $B_r = 8$Nms and $K_r = 15$Nm.

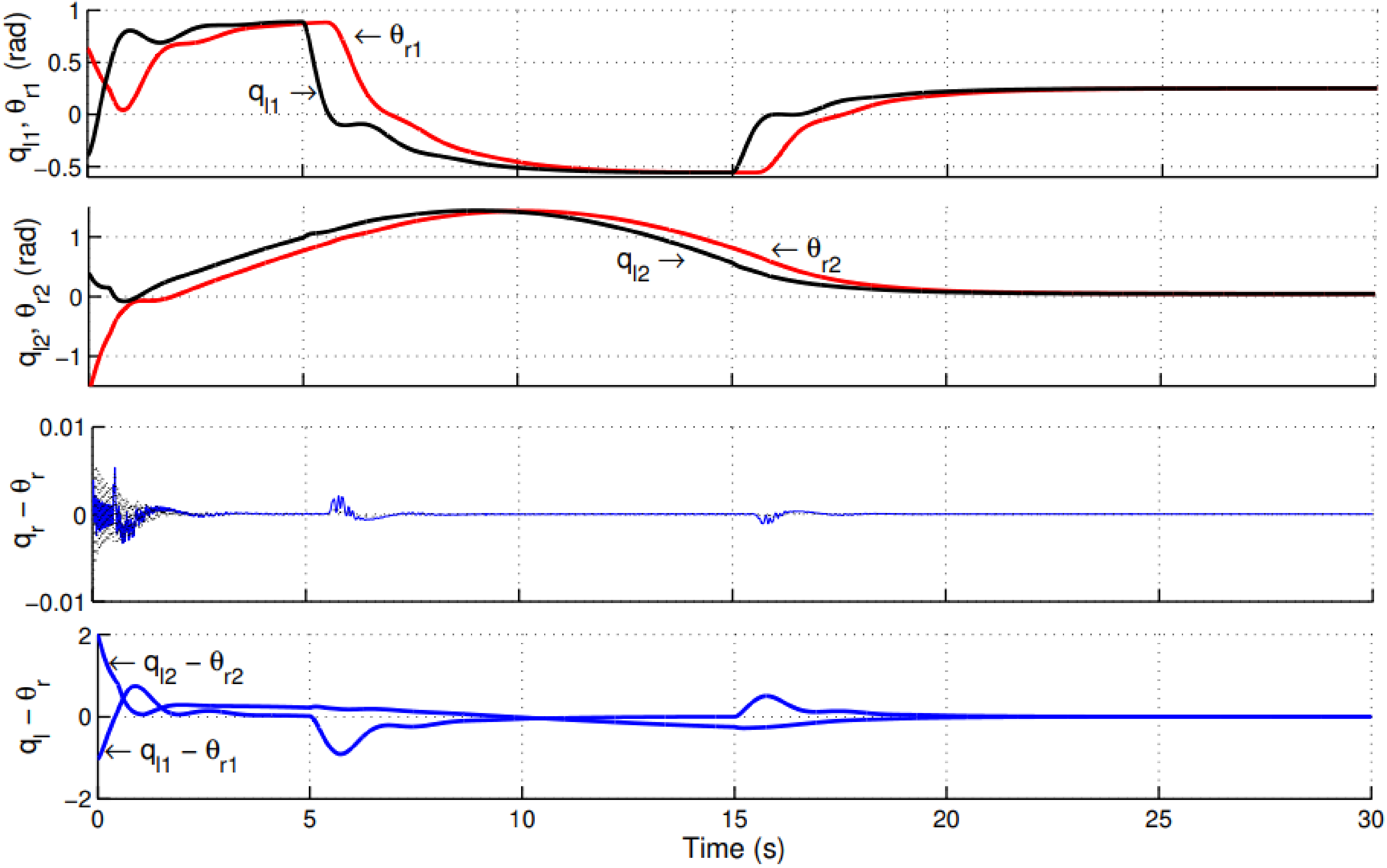


Fig. 5. Local and remote joint positions and position error.

Simulation 2

Control of teleoperators with joint flexibility, uncertain parameters and time-delays[☆]

Emmanuel Nuño[a,*], Ioannis Sarras[b], Luis Basañez[c], Michel Kinnaert[d]

4.2. Dealing with local and remote flexibility

When the local manipulator exhibits joint flexibility, its dynamical behavior (1) transforms to

$$\mathbf{M}_l(\mathbf{q}_l)\ddot{\mathbf{q}}_l + \mathbf{C}_l(\mathbf{q}_l, \dot{\mathbf{q}}_l)\dot{\mathbf{q}}_l + \mathbf{S}_l[\mathbf{q}_l - \boldsymbol{\theta}_l] = \boldsymbol{\tau}_h \tag{16a}$$

$$\mathbf{J}_l\ddot{\boldsymbol{\theta}}_l + \mathbf{S}_l[\boldsymbol{\theta}_l - \mathbf{q}_l] = -\boldsymbol{\tau}_l \tag{16b}$$

where $\mathbf{J}_l \in \mathbb{R}^{n\times n}$ is a diagonal matrix corresponding to the local actuator inertia and $\mathbf{S}_l \in \mathbb{R}^{n\times n}$ is a diagonal and positive definite matrix that contains the local joint stiffness.

Proposition 3. *Consider the teleoperator (16) and (2), controlled by*

$$\boldsymbol{\tau}_l = K_l[\boldsymbol{\theta}_l - \boldsymbol{\theta}_r(t - T_r(t))] + B_l\dot{\boldsymbol{\theta}}_l \tag{17a}$$

$$\boldsymbol{\tau}_r = -K_r[\boldsymbol{\theta}_r - \boldsymbol{\theta}_l(t - T_l(t))] - B_r\dot{\boldsymbol{\theta}}_r \tag{17b}$$