An adaptive controller for nonlinear teleoperators☆

Emmanuel Nuño [a,b,*], Romeo Ortega [c], Luis Basañez [b]

[a] Department of Computer Science, University of Guadalajara, Av. Revolución 1500, 44430 Guadalajara, Mexico
[b] Institute of Industrial and Control Engineering, Technical University of Catalonia, Av. Diagonal 647, 08028 Barcelona, Spain
[c] Laboratoire des Signaux et Systèmes, SUPÉLEC, Plateau de Moulon, 91190 Gif-sur-Yvette, France

2010

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

Emmanuel Nuño, Ioannis Sarras, Luis Basañez and Michel Kinnaert

2012

An adaptive controller for nonlinear teleoperators with variable time-delays☆

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

2012

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

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

2014

Local Dynamic

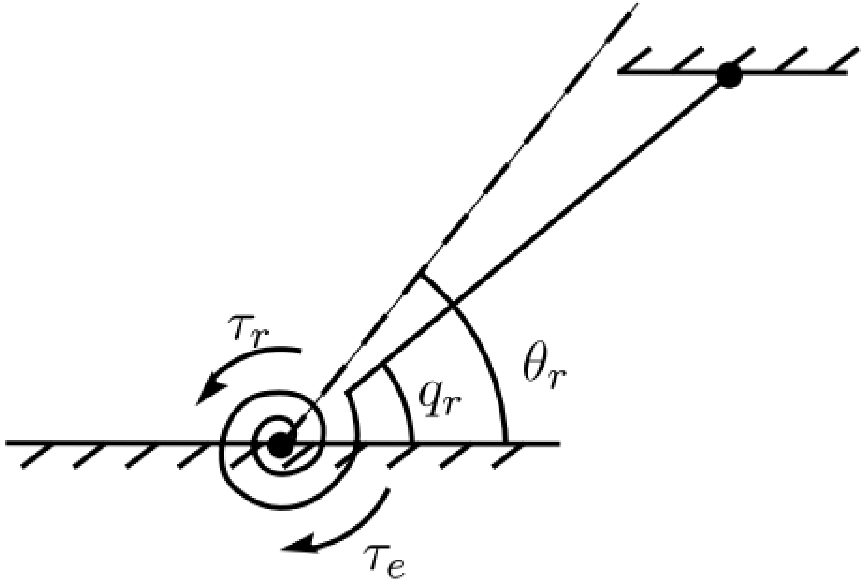
- 2010

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

- 2014

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

Remote Dynamic



- 2010

$$\mathbf{M}_r(\mathbf{q}_r)\ddot{\mathbf{q}}_r + \mathbf{C}_r(\mathbf{q}_r, \dot{\mathbf{q}}_r)\dot{\mathbf{q}}_r + \mathbf{g}_r(\mathbf{q}_r) = \boldsymbol{\tau}_r - \boldsymbol{\tau}_e,$$

- 2014

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

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

$\mathbf{J}_r \in \mathbb{R}^{n\times n}$ is a constant diagonal matrix representing the remote actuator moments of inertia, $\mathbf{S}_r \in \mathbb{R}^{n\times n}$ is a constant diagonal and positive definite matrix that contains the remote joint stiffness,

Error and Synch. Signal

- 2010

$$\mathbf{e}_l = \mathbf{q}_r(t-T) - \mathbf{q}_l; \qquad \mathbf{e}_r = \mathbf{q}_l(t-T) - \mathbf{q}_r.$$

$$\mathbf{s}_i = \dot{\mathbf{q}}_i + \lambda \mathbf{q}_i,$$

- 2014

$$\mathbf{e}_l := \mathbf{q}_l - \boldsymbol{\theta}_r(t-T_r), \qquad \mathbf{e}_r := \boldsymbol{\theta}_r - \mathbf{q}_l(t-T_l), \tag{4}$$

$$\epsilon_l = \dot{\mathbf{q}}_l + \lambda \mathbf{e}_l,$$

where $\lambda \in \mathbb{R}_{>0}$ is a control gain.

Adaptive Control Law

- 2010

$$\bar{\tau}_i = \mathbf{K}_i \epsilon_i - \mathbf{B}\dot{\mathbf{e}}_i$$

- 2014

$$\tau_l = \mathbf{Y}_l(\mathbf{q}_l, \dot{\mathbf{q}}_l, \dot{\mathbf{e}}_l, \mathbf{e}_l)\hat{\phi}_l + \mathbf{K}_l \epsilon_l + \mathbf{B}\dot{\mathbf{e}}_l.$$

$$\mathbf{M}_l(\mathbf{q}_l)\dot{\epsilon}_l + [\mathbf{C}_l(\mathbf{q}_l, \dot{\mathbf{q}}_l) + \mathbf{K}_l]\epsilon_l + \mathbf{B}\dot{\mathbf{e}}_l = \mathbf{Y}_l\tilde{\phi}_l + \tau_h,$$

$$\tau_r = -\lambda \mathbf{B}\dot{\mathbf{e}}_r - \mathbf{K}_r\dot{\theta}_r,$$

Simulation

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

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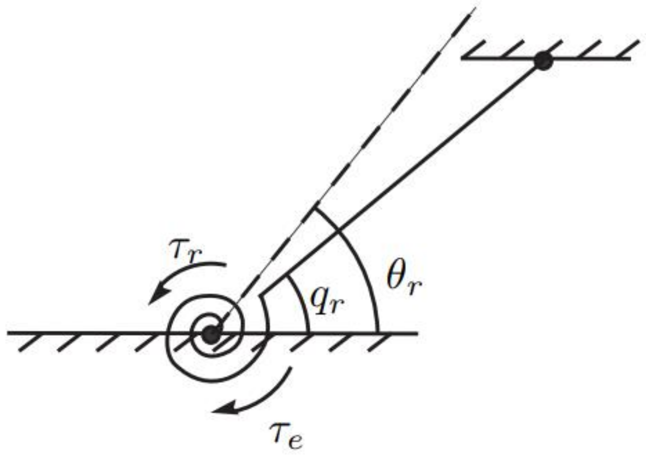
Non-Linear Dynamic



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

Remote: **Flexible**

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

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

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

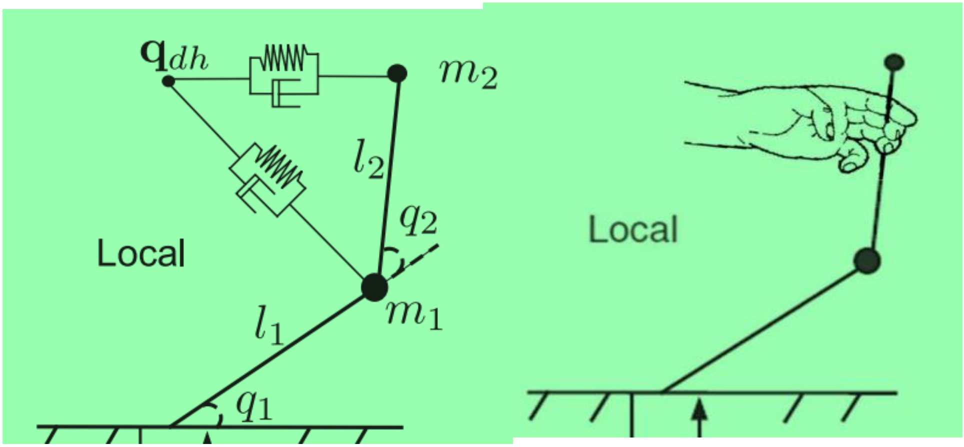
of link k of manipulator i, with $k \in \{1, 2\}$. The Coriolis and centrifugal effects are modeled by $\mathbf{C}_i(\mathbf{q}_i, \dot{\mathbf{q}}_i) = [C_{mn}]$ and are given by $C_{11} = -2\beta_i \mathrm{s}_{2_i} \dot{q}_{2_i}$, $C_{12} = -\beta_i \mathrm{s}_{2_i} \dot{q}_{2_i}$, $C_{21} = \beta_i \mathrm{s}_{2_i} \dot{q}_{1_i}$ 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 $\mathbf{J}_r = 0.2\mathbf{I}\text{Kgm} \in \mathbb{R}^{2\times 2}$, the stiffness of the remote flexible joints is $\mathbf{S}_r = 500\mathbf{I}\text{Nm} \in \mathbb{R}^{2\times 2}$. The physical parameters for the manipulators are: the length of links $l_{1_i} = l_{2_i} = 0.38\text{m}$; the masses of the links are $m_{1_l} = 3.5\text{Kg}$, $m_{2_l} = 0.5\text{Kg}$, $m_{1_r} = 0.5\text{Kg}$ and $m_{2_r} = 0.35\text{Kg}$. 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



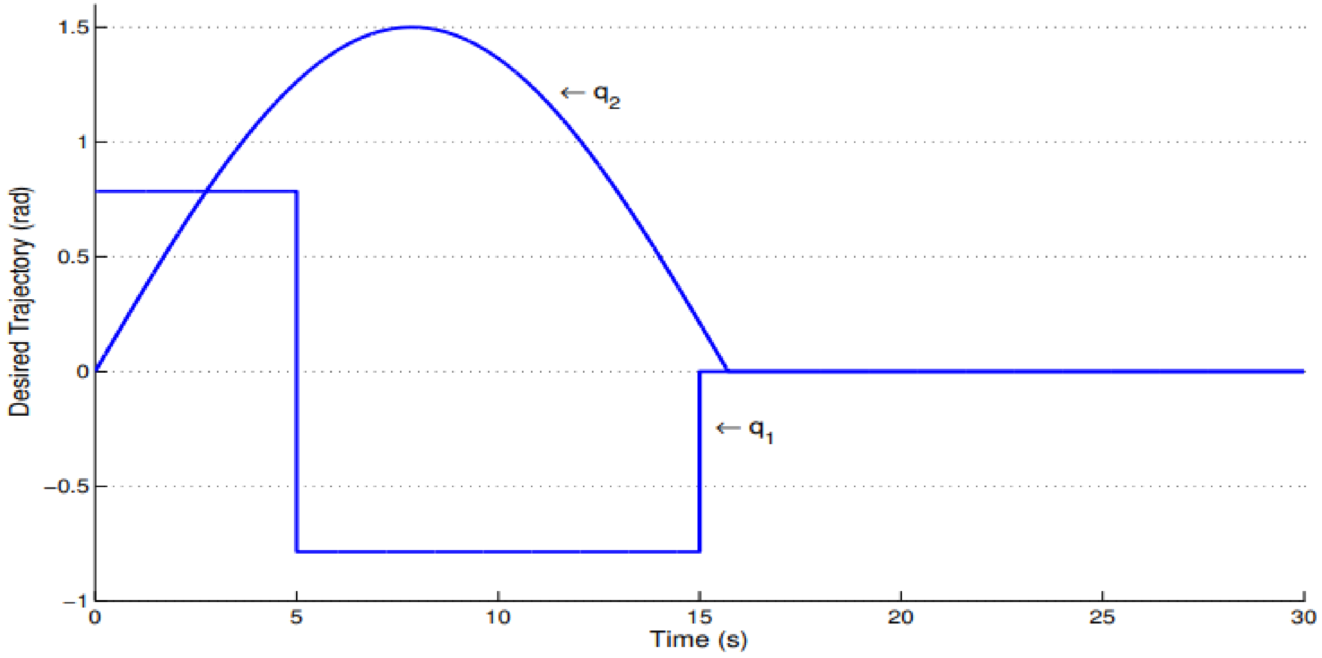


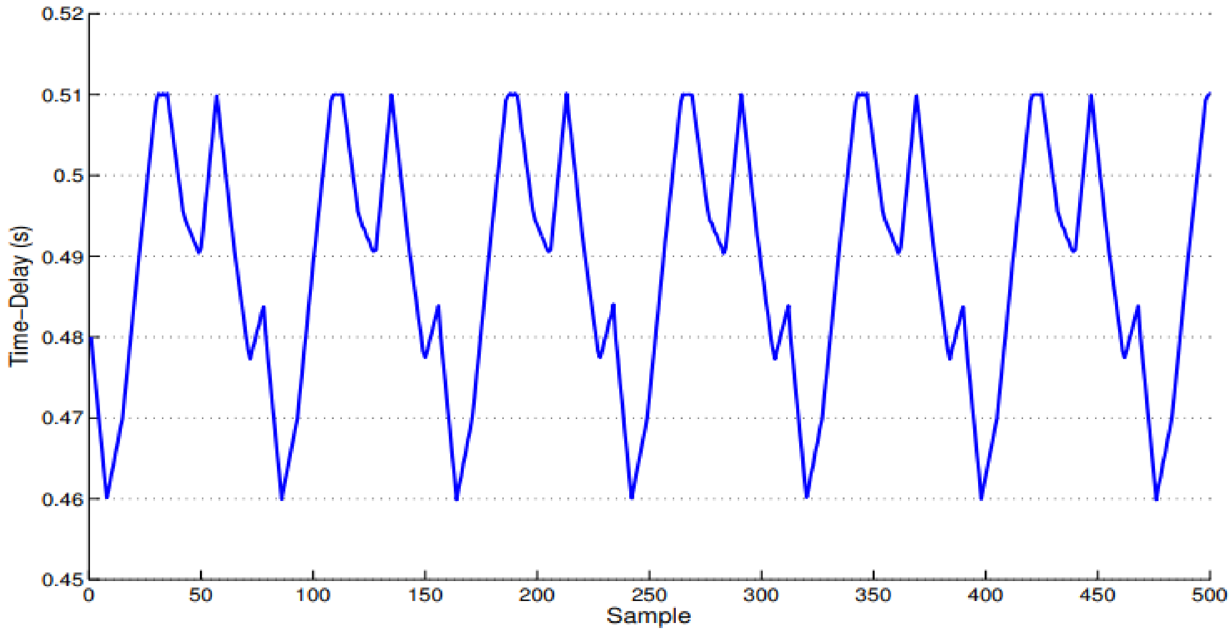
Fig. 3. Desired trajectory of the human operator.

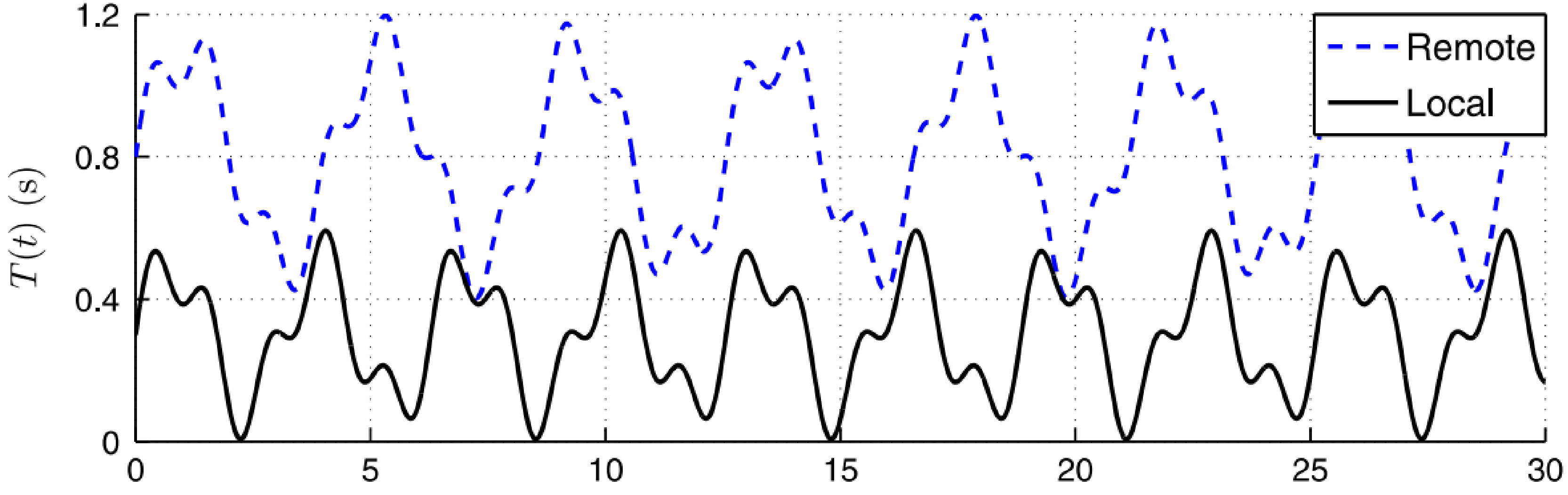
$$\tau_h = K_h(q_d - q_l) - d\dot{q}_l$$

Variable Time Delay

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

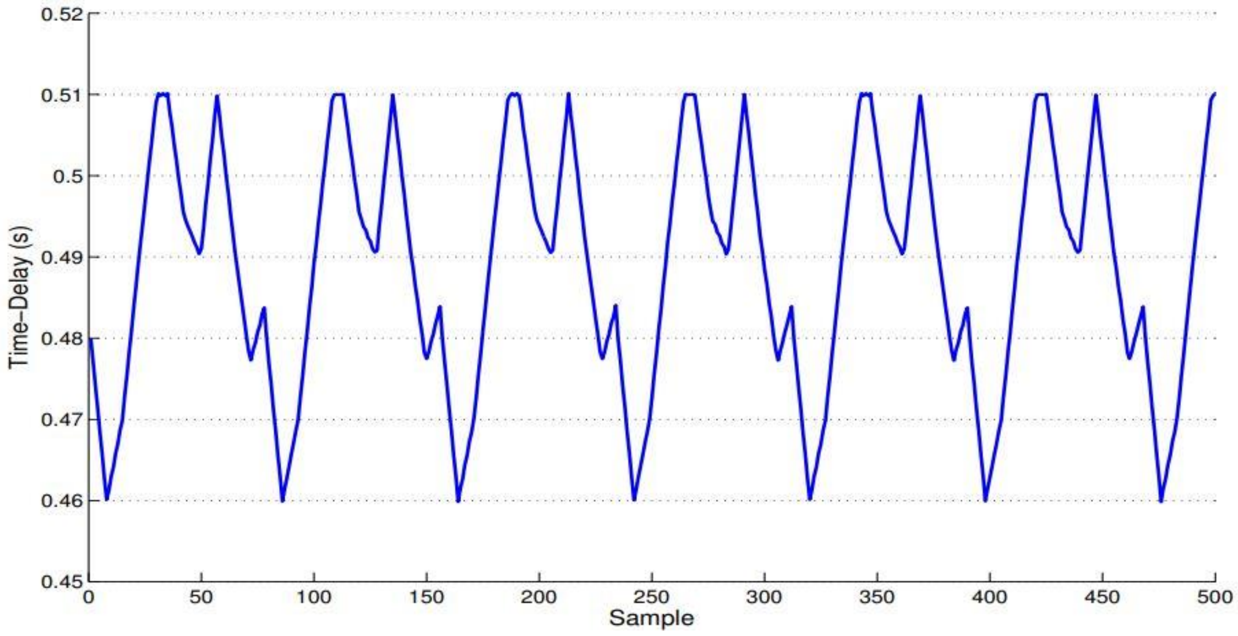
$${}^{*}T_i = 0.55\text{s}$$

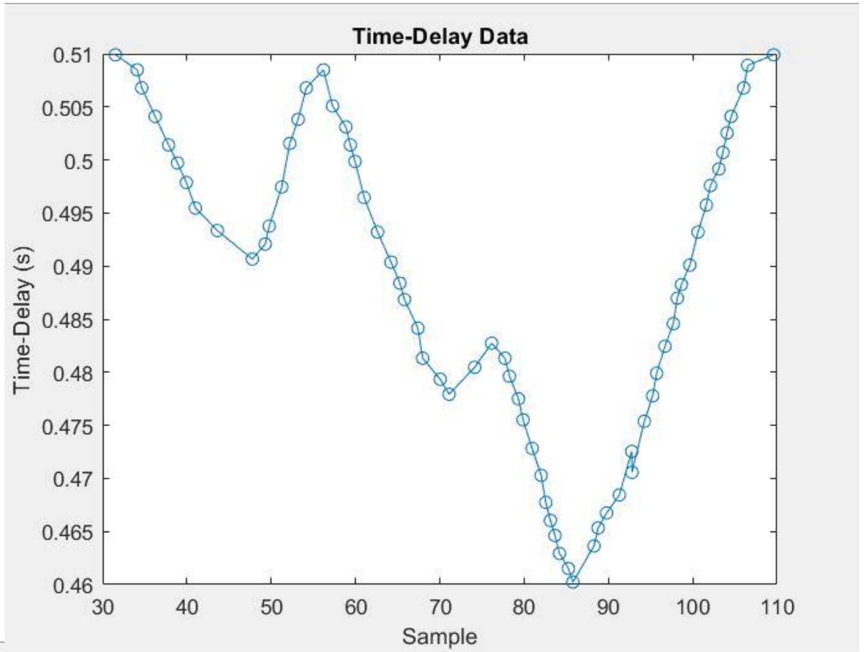


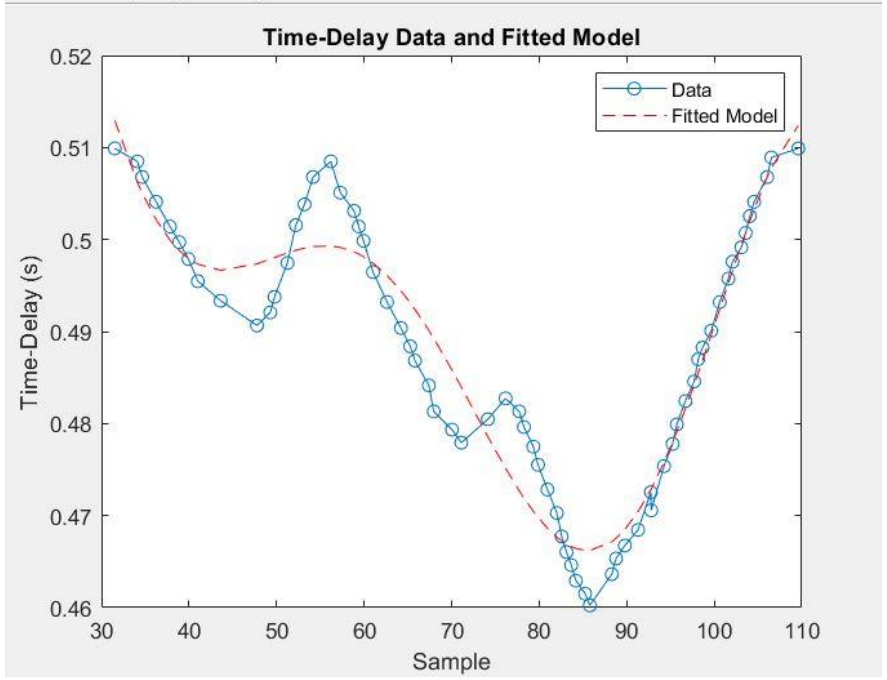


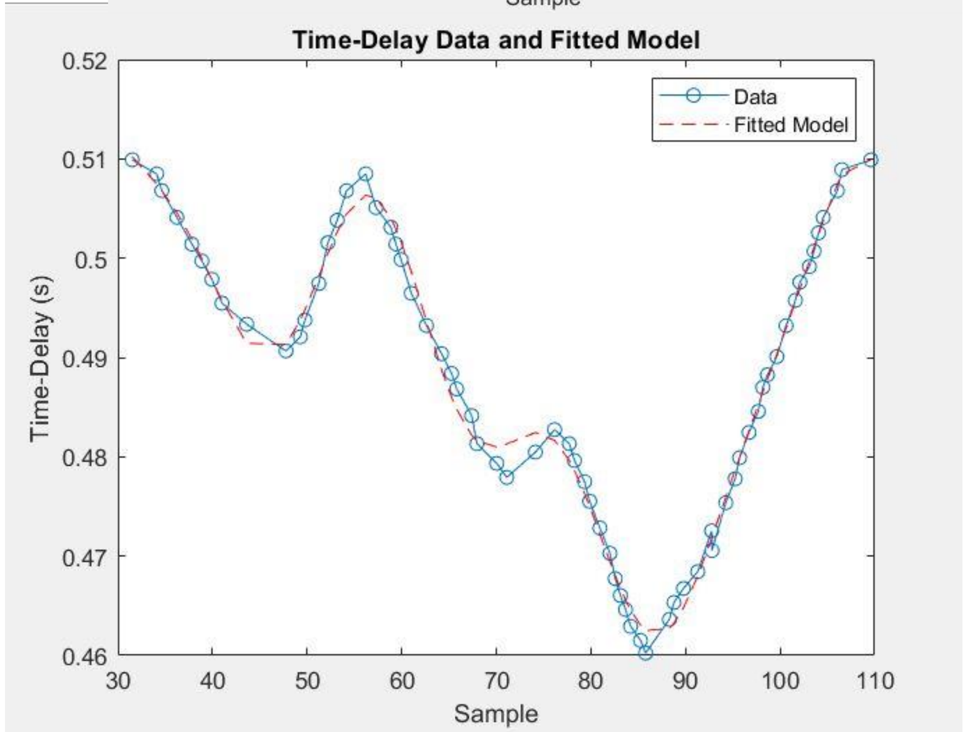
$$T_l(t) = 0.3 + 0.2 \ \sin(2t) + 0.1$$

$$T_r(t) = 0.8 +$$
$$0.3 \ \sin(1.5t) + 0.1 \ \sin(5t).$$


Time-Delay (s)
Sample


Time-Delay Data
Time-Delay (s)
Sample


Time-Delay Data and Fitted Model
Data
Fitted Model
Time-Delay (s)
Sample


Time-Delay Data and Fitted Model
Data
Fitted Model
Time-Delay (s)
Sample

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.