Cascade Control for Telerobotic Systems
Serving Space Medicine

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Abstract: Long distance teleoperation formulates a current control problem task yet to be solved, primarily due to the difficulty to compensate for signal latency. Predictive and model-based control can only give satisfying results if proper description of the system’s behavior is provided. The interdisciplinary field of telesurgery has become a focal point of technology-extended medicine, where master–slave type control over large distances poses significant challenges. Innovative solutions are required to deal with the modeling human teleoperation and varying communication quality parameters. In this paper, we investigate the feasibility of a more straightforward, classical control solution based on Kessler’s Extended Symmetrical Method, formulated in a cascade control approach to tackle the problems caused by latency and uncertainties in a modeled telesurgical robot system.

Keywords: Teleoperation; Cascade control; Time-delay control; Surgical robotics.

1. MEDICAL TELEROBOTICS IN SPACE

Robotic surgery rapidly advances on Earth, creating an increasing demand for effective teleoperation techniques, as professionals realize their effectiveness in extending the reach of modern health care to remote areas. Parallel, the research community has been dealing with space application of telerobotics since the early days of the field. To cope with the difficulties of endoscopic surgery in weightlessness and the extensive space-system requirements, a three-layered mission architecture was proposed earlier, in order to achieve the highest degree of performance possible by combining robotic and human surgery (Haidegger and Benyó [2008]). Depending on the physical distance between the spacecraft and the ground control center, different telepresence technologies may provide the best task performance:

1. Real-time telesurgery: up to 2 s round trip delay; 400,000 km (Earth–Moon distance).
2. Telementoring: up to 50–70 s; 10 million km.
3. Consultancy teleradiology: possible to reach Mars with 5–44 min latency; 46–399 million km.

The effectiveness of real-time control strategies and communication techniques degrades significantly with the increase of latency. Special control algorithms and engineer-

* This work was supported in part by the National Office for Research and Technology (NKTH), Hungarian National Scientific Research Foundation grant OTKA CK80316. It is connected to the scientific program of the " Development of quality-oriented and harmonized R+D+I strategy and functional model at BME" project, supported by the New Hungary Development Plan (Project ID: TAMOP-4.2.1/B-09/1/KMR-2010-0002).

Write the following equation:

\[ W_{Op} = k_{Op} \frac{(\tau_s s + 1)e^{-s\tau}}{(\tau_s s + 1)(\tau_n s + 1)}. \]

where \( k_{Op} \) is the operator’s static gain, the \( e^{-s\tau} \) term reflects the pure time delay caused by the human sensory system limitations, \( \tau_l \) is the lead time constant (relative rate-to-displacement sensitivity), \( \tau_n \) is the lag time constant, \( \tau_m \) the neuromuscular and activation mechanism lag time (McRuer and Jex [1967]). This is called the crossover model that yields to the widely applied Fitts’ law assuming zero physiological time delay (Fitts [1992]).
3. ROBOT MODEL FOR TELEOPERATION SCENARIOS

Let us assume that the robot has rigid links with typical mechanical properties. The servo motors are driven by the joint controller according to the commands from the master side. In telesurgery, it is desirable to minimize the load to the patient’s tissue, therefore force control may be used. A simple dynamic model of the manipulator, incorporating the deviation of the tool from the master controller’s position is:

\[ f_t = k_g (x_s(t) - x_M(t - T_{lat})) + B_g (x_s(t) - x_M(t - T_{lat})) + M_g \ddot{x}_s(t), \]

where \( x_s \) is the Cartesian position of the slave, \( x_M \) is the Cartesian position of the master, \( k_g \) is the stiffness of the slave manipulator and \( T_{lat} \) is the latency of the communication network (Kawashima et al. [2008]).

Tissue characteristics are considered through Fung’s exponential force–stretch ratio curve, deriving the relation between Lagrangian stress and stretch ratio:

\[ f_T = p \left( e^{q x_s(t)} - 1 \right), \]

where \( p \) and \( q \) are tissue-specific constants, determined to be 0.2 and 400, respectively for in-vivo abdominal tissue (Kawashima et al. [2008]). In our target application, strains are low, therefore the tissue behavior can be modeled as linear. \( G(s) \) represents the linearized, frequency domain equivalent of (3). The slave robot can be modeled together with an observer to determine \( f_T \). Deviation originating from the physical realization of the robot’s mechanical structure (imperfections and frictions) have been omitted from the model, resulting the Transfer Function (TF):

\[ W_S = \frac{(k_g + B_g)s + G(s)}{s(M_g s^2 + B_g s + k_g + G(s))}. \]

4. CASCADE CONTROLLER FOR A TELESURGICAL ROBOT

A realistic teleoperation system suffers from time delays during communications between the master (controller) and slave side (effector system). Unless the process is significantly slower than the latency, the control lag time can cause the deterioration of the control quality. Even general instability can occur due to unwanted power generation in the communications. The use of empirical design methods is justified with the need for simple and quick algorithms in cases when model predictive control may be cumbersome to apply. Since a human physician controls the robot, it is extremely difficult to develop plausible model for their behavior from the control point of view.

Cascade control can improve control system performance over single-loop control. Advantages of cascade control have been widely studied and published, both for telesurgical and generic space robotic applications (Hirzinger et al. [1989]).

4.1 Empirical design approach—Kessler’s methods

It is well known that empirical methods can provide a solution for automatic system calibration, following the mainstream approach of control theory. Based on (1), the inner part of the cascade control scheme (robot) can be described in a compact form (Haidegger et al. [2010]). As proposed by Kessler (Kessler [1958]), the class of plants characterized by TF:

\[ H_P(s) = \frac{k_p}{s(1 + sT_1)(1 + sT_Σ)}, \]

\[ H_P(s) = \frac{k_p}{s(1 + sT_1)(1 + sT_2)(1 + sT_Σ)}, \]

can be controlled through empirical methods (Preitl et al. [2002]). In (5) and (6) \( T_Σ \) is a small time constant or aggregated time constant corresponding to the sum of parasitic time constants, \( T_Σ < T_2 < T_1 \). The use of a PI or PID controller having the TF:

\[ H_C(s) = \frac{k_c}{s(1 + sT_{C1})(1 + sT_{C2})} \]

can ensure acceptable performance (Astrom and Hagglund [1995]). \( T_Σ \) can also include the time constants used to approximate the time delay. In (6), the process pole \( (p_1 = -1/T_1) \) may be compensated by the controller zero \( (z_1 = -1/T_{C2}) \) in order to obtain the desired open loop TF in the form:

\[ H_0(s) = H_C(s)H_P(s) = \frac{k_0(1 + sT_{C1})}{s^2(1 + sT_Σ)}, \]

with \( k_0 = k_p k_c \). Extensions of the Kessler methods were proposed in the literature (Preitl and Precup [1999], Vranic et al. [2001]), and the Extended Symmetrical Optimum method (ESO) was derived, where:

\[ k_c = \frac{1}{k_p β^2 T_{Σ}^2}, \]

\( T_{C1} = βT_Σ \) and \( T_{C2} = T_1 \).

Tuning parameters are directly correlated to the desired control system performance indices. The value of \( β \) is typically chosen to be in the \([4, 19]\) interval. It is possible to optimize \( β \) for maximum Phase Margin (PM) for any given \( k_p \) constant. Depending on \( β \), the closed loop systems poles \((p_1, p_2, p_3)\) can be (Preitl and Precup [2000]):

- \( p_1, p_2 \) are complex conjugated, if \( β < 9 \),
- \( p_{1,2,3} \) are real and equal, if \( β = 9 \),
- all poles are real and distinct for \( β > 9 \), but the system remains oscillatory.

The open loop TF being given as:

\[ H_0(s) = \frac{1 + βT_Σ s}{β^2 T_{Σ}^2 s^2(1 + T_Σ s)}. \]

5. APPLICATION ORIENTED CONTROLLER DESIGN SOLUTIONS

Considering the discussed challenges, we were focusing on a classical control approach to provide a simple, universal and scalable solution (Haidegger et al. [2010]). We employed Kessler’s ESO method and developed its first embedded application in the broader domain of robotics.
In the case of a cascade structure, the data of the inner loop gives feedback to the outer loop, but no a priori knowledge about the inner loop’s dynamics is required to design the outer controller. On the other hand, it is possible to explicitly consider the remote dynamics in the outer controller in order to predict the inner behavior (Arcara and Melchiorri [2002]). This can be based on the well-known Smith predictor scheme, or similar predictors Lantos [2001].

5.1 Realization of control methods

The method has been tested in simulations to show its effectiveness. The models for teleoperation have been described, and implemented under MATLAB R2009b and Simulink 7.1 environment.

Master–slave robots are typically used in a discrete position-controlled mode. During the evaluation, a critical factor was to ensure that the PM is between 45–60◦, where the system is inherently stable, and we also set requirements for reasonable performance in terms of overshoot, settling time, and proximity of performance. This allows for 12 Hz control cycle (comparable to the performance of current optical tracking systems).

5.2 Slave side—inner loop

The slave robot can be modeled in accordance with (4):

\[ W_s = \frac{(k_s + B_s s)G(s)}{s(M_s s^2 + B_s s + k_s + G(s))}. \]  

The model in \( s \) domain (assuming constant contact force) being:

\[ G(s) = p(e^{qK} - 1) = \frac{k_t}{s}. \]

However, when \( K = x_s(t)_{\text{const}} \), substituting \( G(s) \) into (11), the plant’s TF becomes:

\[ W_P = \frac{k_1 B_s s + k_1 k_s}{s(M_s s^2 + B_s s + (k_s + k_t))}. \]

We assume a reasonably small slave robot that might be suitable for long duration space missions based on (Kawashima et al. [2008]): \( M_s=0.1 \text{ kg}, B_s=20 \text{ Ns/m}, k_s=400 \text{ and } x_s=0.001 \text{ m}. \) Tissue interaction parameters were chosen similarly: \( p = 0.2 \) and \( q = 400. \)

First, let us employ an input filter on the plant:

\[ W_{P_1} = \frac{1}{k_{G_s+1}}, \]

leading to a filtered plant in the form of (5), with:

\[ k_p = \frac{k_1 k_t}{k_s + k_t} = 0.0938, \]

\[ T_{P_1} = \frac{2(k_s + k_t)}{B_s - \sqrt{B_s^2 - 4M_s(k_s + k_t)}} = 0.0444 \text{s} \] and

\[ T_\Sigma = \frac{2(k_s + k_t)}{B_s + \sqrt{B_s^2 - 4M_s(k_s + k_t)}} = 0.0056 \text{s}. \]

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\[ T_\Sigma = \frac{2(k_s + k_t)}{B_s + \sqrt{B_s^2 - 4M_s(k_s + k_t)}} = 0.0056 \text{s}. \]

### Table 1. Controller performance parameters for the inner loop with different \( \beta_{\text{inner}} \) settings

<table>
<thead>
<tr>
<th>( \beta )</th>
<th>Phase Margin</th>
<th>Overshoot</th>
<th>Setting time</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>36.9◦</td>
<td>0%</td>
<td>0.052 s</td>
</tr>
<tr>
<td>5</td>
<td>41.8◦</td>
<td>0%</td>
<td>0.066 s</td>
</tr>
<tr>
<td>6</td>
<td><strong>45.6◦</strong></td>
<td>0%</td>
<td><strong>0.082 s</strong></td>
</tr>
<tr>
<td>7</td>
<td>48.6◦</td>
<td>0%</td>
<td>0.099 s</td>
</tr>
<tr>
<td>8</td>
<td>51.1◦</td>
<td>0%</td>
<td>0.117 s</td>
</tr>
<tr>
<td>9</td>
<td>53.1◦</td>
<td>0%</td>
<td>0.135 s</td>
</tr>
<tr>
<td>10</td>
<td>54.9◦</td>
<td>0%</td>
<td>0.154 s</td>
</tr>
<tr>
<td>11</td>
<td>56.4◦</td>
<td>0%</td>
<td>0.173 s</td>
</tr>
<tr>
<td>12</td>
<td>57.8◦</td>
<td>0%</td>
<td>0.192 s</td>
</tr>
<tr>
<td>13</td>
<td>59◦</td>
<td>0%</td>
<td>0.212 s</td>
</tr>
<tr>
<td>14</td>
<td>60.1◦</td>
<td>0%</td>
<td>0.231 s</td>
</tr>
<tr>
<td>15</td>
<td>61◦</td>
<td>0%</td>
<td>0.251 s</td>
</tr>
<tr>
<td>16</td>
<td>61.9◦</td>
<td>0%</td>
<td>0.271 s</td>
</tr>
</tbody>
</table>

Good control system performance indices (overshoot, settling time, control error) can be obtained with a PID controller having the TF:

\[ W_{\text{Contr,in}} = \frac{k_{\text{Contr,in}}}{s}(1 + sT_C)(1 + sT_{C2}) \]

applied to the inner control loop.

The following tuning equations—specific to ESO method—lead to the tuning parameters of the PID controller in the inner loop:

\[ k_{\text{Contr,in}} = \frac{1}{\beta^2 \sqrt{\beta \Sigma T_S^2} s} (1 + \beta T_S s + \beta T_S^2 s^2) \]

where \( \beta = \beta_{\text{inner}} \) is the tuning parameter of the inner control loop. The designer can set the value of this parameter to ensure an acceptable compromise in the control system performance indices. The open loop and closed loop TFs (\( W_0 \) and \( W_C \), respectively) derive to be:

\[ W_0 = W_{P_1} W_{\text{Contr,in}} \]

\[ W_C = \frac{1 + \beta T_S s}{(1 + \sqrt{\beta T_S s})(1 + (\beta - \sqrt{\beta}) T_S s + \beta T_S^2 s^2)}. \]

For \( \beta = [4, 9] \), \( W_0 \) contains a complex conjugated pole pair with slightly decreasing absolute values. Therefore it is advisable to apply filtering in accordance with (Preitl and Precup [1999]). Filtering for \( p_{1,2} \) means to compensate for the complex conjugated poles in the \( \beta = [4, 9] \) domain,

\[ W_{P_1} = \frac{1 + (\beta - \beta^2)}{1 + \sqrt{\beta T_S s}(1 + \lambda T_S s)} \]

where \( \lambda = \beta - \beta^2 - 1 \). Then the \( W_{P_1} \) filter is applied, and the closed loop TF of the inner control loop (\( W_{\text{inner}} \)) becomes:

\[ W_{\text{inner}} = W_{P_1} W_C = \frac{1}{(1 + \sqrt{\beta T_S s})(1 + \lambda T_S s)}. \]

Based on the data presented in Table 1, \( \beta_{\text{inner}} \) must be over 5 to ensure 45◦ PM, resulting in inherent stability of the system. Overshoot is 0% in every case due to the fact that we employed a (21) type filter. Based on the experiments, it is advantageous to choose \( \beta_{\text{inner}} = 6 \) for further design calculations, providing the best performance. This allows for 12 Hz control cycle (comparable to the performance of current optical tracking systems).
5.3 Master side—outer loop

The human operator’s model (\( W_{\text{Hum}} \)) in accordance with the crossover model (1) can be obtained using Padé approximation (Lantos [2001]):

\[
W_{\text{Hum}} \approx W_{\text{Hum,Padé}} = k_{p,\text{Hum}} \frac{\omega_c,\text{Hum}^2 - sT_{\text{Hum}}}{s(2 + sT_{\text{Hum}})},
\]

(23)

where \( T_{\text{Hum}} \) is the human operator’s physiological latency. Typically, \( T_{\text{Hum}} = 0.1 \) s and \( k_{p,\text{Hum}}\omega_c,\text{Hum} = 1 \).

Filtering in the outer loop can be used to speed up the system. We compensate for the denominator of the inner closed loop transfer function in (22). The outer loop filter’s TF is chosen to be:

\[
W_{F,\text{out}} = \frac{1 + sT_{\text{Comp}}}{1 + sT_F},
\]

(24)

where \( T_F \) is a filter time constant. \( T_{\text{Comp}} \) is set to compensate for the largest time constant in (22):

\[
T_{\text{Comp}} = \max (T_{P1}, T_{P2}) = \max \left( \sqrt{3}T_{\Sigma}, \lambda T_{\Sigma} \right)
\]

(25)

\[
\begin{align*}
\text{if} & \quad 1 < \beta \leq 3 + 2\sqrt{2} \\
\lambda T_{\Sigma} & = (\beta - \sqrt{2})T_{\Sigma} \quad \text{if} \quad \beta > 3 + 2\sqrt{2},
\end{align*}
\]

In addition, \( T_F \) is a small filter time constant fulfilling the condition:

\[
0 < T_F \ll \min \left( \sqrt{3}T_{\Sigma}, \lambda T_{\Sigma} \right).
\]

(26)

The TF of the outer loop process is derived in the following form:

\[
W_{P,\text{out}} = W_{\text{Hum}} W_{P,\text{out}}(\text{Latency}) W_{\text{Inner}} W_{\text{Latency}}
\]

\[
= \frac{s(1 + sT_F)(1 + sT_{P2})}{k_{p,\text{out}} sT_{\text{out}}},
\]

(27)

\[
W_{p,\text{out}} = \frac{k_{p,\text{Hum}} \omega_c,\text{Hum}}{1 + sT_{\text{out}}},
\]

\[
T_{\text{Out}} = \frac{T_{\text{Hum}} - 2T_d}{2}.
\]

The TF defined in (27) can be used in the design and tuning of the outer loop controller with TF \( W_{\text{Contr,}\text{out}} \). The open loop and closed loop TFs, \( W_{o,\text{out}} \) and \( W_{c,\text{out}} \) are:

\[
W_{o,\text{out}} = W_{\text{Contr,ou}} W_{P,\text{out}} \quad \text{and} \quad W_{c,\text{out}} = \frac{W_{o,\text{out}}}{1 + W_{o,\text{out}}},
\]

(28)

Using (26), a simplified version of the TF in (27) can be derived:

\[
W_{p,\text{out}} \approx \frac{k_{p,\text{out}}}{s(1 + T_{F})} e^{-sT_F},
\]

(29)

where \( T_{F,\text{out}} = T_F + T_{P2} \). Using Padé approximation the TF of the outer loop process is approximated as:

\[
W_{p,\text{out}} \approx W_{p,\text{out},\text{Padé}}
\]

\[
= W_{\text{Hum,Padé}} W_{\text{Padé}} W_{\text{Inner}} W_{\text{Padé}}
\]

\[
= \frac{k_{p,\text{Padé}}(1 - sT_{\text{Hum}})(1 - sT_{\text{Padé}})^2}{s(1 + sT_F)(1 + sT_{P2})(1 + sT_{\text{Hum}})(1 + sT_{\text{Padé}})^2}.
\]

(30)

Fig. 2. The robustness of Kessler’s method proven through its ability to compensate for latencies up to 0.5 s, originally not incorporated in the system model.

5.4 Solutions to handle time delay in telesurgery

In this Section, we discuss plausible options to deal with the outer controller design. Different approaches have been investigated, simulated and evaluated to determine their usability in the given cascade structure for teleoperation. Our previous experiments showed that neither the classical Ziegler–Nichols method, nor the straightforward application of Kessler’s method gave satisfying results in terms of control parameter requirements Haidegger [2010].

Stretching Kessler’s robustness

It is possible to overcome the limitation of the original concept by violating the condition that the largest time constant is greater than the sum of the rest. While the extended Kessler method (Astrom and Hagglund [1995]) only guarantees control over the overshoot and settling parameters if the largest time constant is compensated, the robustness of the design method can be exploited. Understandably, this will return the same results as the previous (classical) method for \( T_d \leq 0.0218 \), but will also give stable solutions for larger latencies. Fig. 1a,b show the results for \( T_d = 0.1 \), the step response and bode plot for \( \beta_{\text{Outer}} = [4, 16] \) values. \( \beta_{\text{Inner}} \) was set to the optimal value, 6. The best results were acquired at \( \beta_{\text{Outer}} = 6 \), where \( \sigma = 33\% \) and \( \tau = 1.28 \) s. The PM is increasing along with \( \beta_{\text{Outer}} \), as the system is getting slower and slower due to the nature of combined time constant approximation. With increasing time delay, only the settling time grows (Fig. 1c). For the desired maximum design constraint of 1 s latency (with \( \beta_{\text{Outer}} = 6 \)), this method gives \( \sigma = 33\% \) and \( \tau = 8.11 \) s, which is unacceptable for a teleoperational surgical application.

It is also possible to test the robustness of Kessler’s method through not incorporating the latency in \( T_{\Sigma} \). In this case, applying the previous \( \beta \) settings, the controller will be unstable. However, the extreme choice of the parameters \( (\beta_{\text{Inner}} = \beta_{\text{Outer}} = 16) \) leads to a stable controller for up to 0.5 s through slowing down the system, as shown in Fig. 2. In fact, latency over 0.2 s results in an under-damped system.
Phase Margin
9.5%
12.1%
1.06 s
Overshoot
17.4%
20%
33%
2.69 s
37%
3.06 s
2.62 s
1.19 s
21%
3 s
41.5
0.57 s
2.71 s
45.3
19%
0.84 s
7.4%
19%
0.92 s
25%
47.9
0%
41
20%
2%
3.14 s
50.6%
Settling time
2.61 s
out
0.99 s
18.4%
1.12 s
Overshoot
8.6%
8%
20%
0.47 s
32.5%
48.7
2.79 s
Settling time
out
8.9%
25%
21%
24%
2.95 s
11%
3.04 s
2.67 s
1.26 s
37%
10%
3.19 s
A
0.61 s
out
42.3
95.3%
2.9 s
23%
25%
10%
2.54 s
Fig. 1. a) Step response of the whole closed loop system with different $\beta_{\text{Outer}}$ settings employing the stretched version of Kessler’s method. $T_d$ was 0.1 s. b) Bode plot of the system with the same settings. c) Step response of the system with $\beta_{\text{Inner}} = \beta_{\text{Outer}} = 6$ and $T_d = 0.1$–1 s.

Table 2. Controller performance parameters with different $\beta_{\text{Outer}}$ settings

<table>
<thead>
<tr>
<th>$\beta_{\text{Outer}}$</th>
<th>Phase Margin</th>
<th>Overshoot</th>
<th>Settling time</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>41°</td>
<td>43%</td>
<td>0.37 s</td>
</tr>
<tr>
<td>5</td>
<td>41.5°</td>
<td>37%</td>
<td>0.54 s</td>
</tr>
<tr>
<td>6</td>
<td>42.3°</td>
<td>33%</td>
<td>0.47 s</td>
</tr>
<tr>
<td>7</td>
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<td>30%</td>
<td>0.61 s</td>
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<td>8</td>
<td>44.3°</td>
<td>27%</td>
<td>0.69 s</td>
</tr>
<tr>
<td>9</td>
<td><strong>45.3°</strong></td>
<td><strong>25%</strong></td>
<td><strong>0.77 s</strong></td>
</tr>
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<td>10</td>
<td>46.2°</td>
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<td>0.84 s</td>
</tr>
<tr>
<td>11</td>
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<td>12</td>
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<td>21%</td>
<td>0.99 s</td>
</tr>
<tr>
<td>13</td>
<td>48.7°</td>
<td>20%</td>
<td>1.06 s</td>
</tr>
<tr>
<td>14</td>
<td>49.4°</td>
<td>19%</td>
<td>1.12 s</td>
</tr>
<tr>
<td>15</td>
<td>50.1°</td>
<td>18%</td>
<td>1.19 s</td>
</tr>
<tr>
<td>16</td>
<td>50.8°</td>
<td>17%</td>
<td>1.26 s</td>
</tr>
</tbody>
</table>

This analysis leads to the conclusion that better methods are required to reach the 2 s round-trip latency tolerance for safe and effective control.

**Kessler’s method with Smith predictor** The classical Smith predictor is a model-based prediction method which handles the time delay outside of the control loop and allows a feedback design based on a delay-free system Lantos [2001]. It is possible to apply the Smith predictor concept to (27), where:

$$W_{\text{Contr}}\text{out} \left(1 + W_{\text{Contr}}\text{out} W_{\text{P}}\text{out} e^{-s T_d}\right).$$

(31)

Similar conditions have been simulated than before, and in the case of $T_d = 0.1$ s, the deriving system performs better than in the previous cases. Table 2 summarizes the numeric results for $\beta_{\text{Inner}} = 6$, employing 5th order Padé approximation for the latency. It can be seen that $\beta_{\text{Outer}} = 9$ gives the best results along the pre-defined criteria.

With this controller structure, it is finally possible to properly address issues with large latencies (e.g., $T_d = 2$ s, as targeted before). To ensure the smooth hold phase of the system, higher order (> 5th) Padé approximation was used. This also increased the overshoot, therefore a rational compromise was chosen. From the application point of view, the amplitude of the oscillation ($A_{\text{max}}$) during the hold phase can be critical, thus it is a limiting factor regarding the choice of the order and the overshoot. It has been determined to only allow a maximum of 10% overshoot during the hold phase, therefore (> 15th) order Padé approximation should be used based on Table 3.

Our previous considerations for $\beta$ are valid here as well, therefore $\beta_{\text{Inner}} = 6$ provides a rational compromise between rise-time and overshoot. With 15th order Padé approximation the effect of the $\beta_{\text{Outer}} = [4, 16]$ parameter on the system is shown in Fig. 3. The smoothing effect of higher $\beta$ in return of slowing down the system is displayed numerically in Table 4. The optimal parametrization of the control structure for extreme teleoperation with 2 s latency has been derived: $\beta_{\text{Outer}} = 6$ and $\beta_{\text{Outer}} = 9$ result in a system with $\tau = 2.61$ s and $\sigma = 25\%$, while the initial oscillation does not exceed 10%. According to the preliminarily defined conditions, this is suitable to support a basic teleoperation setup.

6. CONCLUSIONS

Teleoperation controller design has a huge role in providing the high quality control signals and sensory feedback...
to facilitate surgery over the time-delay network. We proposed a cascade control structure employing empirical controller design to address the challenges of a system with large and probably varying latencies; with robot assisted surgery, fast and reliable control methods are to be used that can adapt to the changing environment.

We also developed a framework for the application of different telemedicine technologies that could be most beneficial for long duration on-orbit missions, or on board of the International Space Station. Particularly, our solution focuses on the handling of delays during real-time teleoperation of a remote surgical robot. In addition, modeling approaches were discussed, and simplified human and machine representations were derived to accommodate long distance telesurgical applications. We have shown that a cascade control structure relying on empirical design can be effectively used to serve a realistically modeled telesurgical system. A suitable controller was designed based on the extension of Kessler’s methods in the inner loop, employing a predictive technique in the outer loop.

As many different solutions have been investigated for bilateral teleoperation scenarios (Hokayem and Spong [2006]), the future research fill focus such solutions to be implemented with our structure. Also, a more complex tissue model will be incorporated on the basis of (Misra et al. [2008]). Other algorithms (soft computing, modern control paradigms) will be used in the outer loop (Precup and Preitl [2007]). Time varying latencies in today’s Internet network represent further technological challenges that need to be addressed (Sankaranarayanan et al. [2007]).

REFERENCES


