Preprints of the 18th IFAC World Congress
Milano (Italy) August 28 - September 2, 2011

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 a more straight-forward, 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 telemedicine: possible to reach Mars with 5–44 min latency; 56–399 million km.

The effectiveness of real-time control strategies and communication techniques degrades significantly with the increase of latency. Special control algorithms and engineering solutions have to be applied (e.g., virtual coupling of the remote environment, or predictive displays) to extend the feasibility of telesurgery up to a maximum of 2 s of delay. Beyond that, only semi-real-time mentoring, or off-line consultancy can be provided. Our goal was to investigate the possibility of a controller design that ensures stable operation for the first zone of space telesurgery. In order to design a suitable control scheme for teleoperation, it is necessary to derive the applicable model of the human operator (*master*—M) and the robot (*slave*—S).

⋆ 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: TÁMOP-4.2.1/B-09/1/KMR-2010-0002).

2. HUMAN OPERATOR MODEL IN TELEOPERATION

The generally used model of the operator (or pilot) containing simplifications (e.g., neglecting high frequency terms) with a first-order neuromuscular lag time is:

$$W_{\mathrm{Op}} = k_{\mathrm{Op}} \frac{(\tau_l s + 1)e^{-s\tau}}{(\tau_i s + 1)(\tau_n s + 1)}, \tag{1}$$

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, τ_l is the lead time constant (relative rate-to-displacement sensitivity), τ_i is the lag time constant, τ_n 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:

$$\begin{aligned}\mathbf{f}_{\mathrm{S}} &= k_{\mathrm{S}}\left(\mathbf{x}_{\mathrm{S}}(t) - \mathbf{x}_{\mathrm{M}}\left(t - T_{\mathrm{lat}}\right)\right) \\ &+ B_{\mathrm{S}}\left(\dot{\mathbf{x}}_{\mathrm{S}}(t) - \dot{\mathbf{x}}_{\mathrm{M}}\left(t - T_{\mathrm{lat}}\right)\right) + M_{\mathrm{S}}\ddot{\mathbf{x}}_{\mathrm{S}}(t), \qquad (2)\end{aligned}$$

where $\mathbf{x}_{\mathrm{S}}$ is the Cartesian position of the slave, $\mathbf{x}_{\mathrm{M}}$ is the Cartesian position of the master, k_{S} 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:

$$\mathbf{f}_T = p\left(e^{q\,\mathbf{x}_{\mathrm{S}}(t)} - 1\right), \qquad (3)$$

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):

$$W_{\mathrm{S}} = \frac{\left(k_{\mathrm{S}} + B_{\mathrm{S}}s\right)G(s)}{s\left(M_{\mathrm{S}}s^2 + B_{\mathrm{S}}s + k_{\mathrm{S}} + G(s)\right)}. \qquad (4)$$

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:

$$H_P(s) = \frac{k_p}{s\left(1 + sT_1\right)\left(1 + sT_\Sigma\right)}, \text{ or} \qquad (5)$$

$$H_P(s) = \frac{k_p}{s\left(1 + sT_1\right)\left(1 + sT_2\right)\left(1 + sT_\Sigma\right)}, \qquad (6)$$

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, $T_\Sigma < T_2 < T_1$). The use of a PI or PID controller having the TF:

$$H_C(s) = \frac{k_c}{s}\left(1 + sT_{C1}\right)\left(1 + sT_{C2}\right) \qquad (7)$$

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:

$$H_0(s) = H_C(s)H_P(s) = \frac{k_0\left(1 + sT_{C1}\right)}{s^2\left(1 + sT_\Sigma\right)}, \qquad (8)$$

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

$$k_c = \frac{1}{k_p \beta^{\frac{3}{2}} T_\Sigma^2}, \; T_{C1} = \beta T_\Sigma \text{ and } T_{C2} = T_1. \qquad (9)$$

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]):

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

The open loop TF being given as:

$$H_0(s) = \frac{1 + \beta T_\Sigma s}{\beta^{\frac{3}{2}} T_\Sigma^2 s^2 (1 + T_\Sigma s)}. \qquad (10)$$

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 defined, 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 (σ), the absolute maximum of the signal and settling time (τ_t), the time by the signal reaches the ±2% proximity of its final value.

5.2 Slave side—inner loop

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

$$W_{\mathrm{S}} = \frac{(k_{\mathrm{S}} + B_{\mathrm{S}} s)\, G(s)}{s\,(M_{\mathrm{S}} s^2 + B_{\mathrm{S}} s + k_{\mathrm{S}} + G(s))}. \tag{11}$$

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

$$G(s) = p\left(e^{qK} - 1\right) = \frac{k_t}{s}. \tag{12}$$

However, when $K = x_{\mathrm{S}}(t)_{\mathrm{const}}$, substituting $G(s)$ into (11), the plant's TF becomes:

$$W_P = \frac{k_t B_{\mathrm{S}} s + k_t k_{\mathrm{S}}}{s\,(M_{\mathrm{S}} s^2 + B_{\mathrm{S}} s + (k_{\mathrm{S}} + k_t))}. \tag{13}$$

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 kg, B_{S}=20 Ns/m, k_{S}=400 and $x_{\mathrm{S}} = 0.001$ m. Tissue interaction parameters were chosen similarly: $p = 0.2$ and $q = 400$.

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

$$W_{\mathrm{F\_in}} = \frac{1}{\frac{B_{\mathrm{S}}}{k_{\mathrm{S}} s + 1}}, \tag{14}$$

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

$$k_p = \frac{k_{\mathrm{S}} k_t}{k_{\mathrm{S}} + k_t} = 0.0938, \tag{15}$$

$$T_{P1} = \frac{2(k_{\mathrm{S}} + k_t)}{B_{\mathrm{S}} - \sqrt{B_{\mathrm{S}}^2 - 4M_{\mathrm{S}}(k_{\mathrm{S}} + k_t)}} = 0.0444s \text{ and} \tag{16}$$

$$T_\Sigma = \frac{2(k_{\mathrm{S}} + k_t)}{B_{\mathrm{S}} + \sqrt{B_{\mathrm{S}}^2 - 4M_{\mathrm{S}}(k_{\mathrm{S}} + k_t)}} = 0.0056s. \tag{17}$$

Table 1. Controller performance parameters for the inner loop with different β_{Inner} settings

β	Phase Margin	Overshoot	Settling time
4	36.9°	0%	0.052 s
5	41.8°	0%	0.066 s
6	**45.6°**	**0%**	**0.082 s**
7	48.6°	0%	0.099 s
8	51.1°	0%	0.117 s
9	53.1°	0%	0.135 s
10	54.9°	0%	0.154 s
11	56.4°	0%	0.173 s
12	57.8°	0%	0.192 s
13	59°	0%	0.212 s
14	60.1°	0%	0.231 s
15	61°	0%	0.251 s
16	61.9°	0%	0.271 s

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

$$W_{\mathrm{Contr\_in}} = \frac{k_{\mathrm{Contr\_in}}}{s}(1 + sT_{C1})(1 + sT_{C2}) \tag{18}$$

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:

$$k_{\mathrm{Contr\_in}} = \frac{1}{\beta^2 \sqrt{\beta} k_p T_\Sigma^2},\ T_{C1} = T_{P1},\ T_{C2} = \beta T_\Sigma, \tag{19}$$

where $\beta = \beta_{\mathrm{Inner}}$ 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:

$$W_0 = W_{\mathrm{PF}} W_{\mathrm{Contr\_in}} \text{ and}$$
$$W_C = \frac{1 + \beta T_\Sigma s}{(1 + \sqrt{\beta} T_\Sigma s)\left[1 + (\beta - \sqrt{\beta}) T_\Sigma s + \beta T_\Sigma^2 s^2\right]}. \tag{20}$$

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.

$$W_{\mathrm{F1}} = \frac{1 + \left(\beta - \beta^{\frac{1}{2}}\right) T_\Sigma s + \beta T_\Sigma^2 s^2}{(1 + \beta T_\Sigma s)\,(1 + \lambda T_\Sigma s)}, \tag{21}$$

where $\lambda = \beta - \beta^{\frac{1}{2}} - 1$. Then the W_{F1} filter is applied, and the closed loop TF of the inner control loop (W_{Inner}) becomes:

$$W_{\mathrm{Inner}} = W_{\mathrm{F1}} W_C = \frac{1}{(1 + \sqrt{\beta} T_\Sigma s)(1 + \lambda T_\Sigma s)}. \tag{22}$$

Based on the data presented in Table 1, β_{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 $\beta_{\mathrm{Inner}} = 6$ 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_{Hum}) in accordance with the crossover model (1) can be obtained using *Padé approximation* (Lantos [2001]):

$$W_{\text{Hum}} \approx W_{\text{Hum\_Padé}} = k_{p\_\text{Hum}} \frac{\omega_{c\_\text{Hum}}}{s} \frac{2 - sT_{\text{Hum}}}{2 + sT_{\text{Hum}}}, \tag{23}$$

where T_{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:

$$W_{\text{F\_out}} = \frac{1 + sT_{\text{Comp}}}{1 + sT_F}, \tag{24}$$

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

$$T_{\text{Comp}} = \max\left(T_{P1}, T_{P2}\right) = \max\left(\sqrt{\beta} T_\Sigma,\, \lambda T_\Sigma\right) \tag{25}$$

$$= \begin{cases} \sqrt{\beta} T_\Sigma & \text{if} \quad 1 < \beta \le 3 + 2\sqrt{2} \\ \lambda T_\Sigma = (\beta - \sqrt{\beta} - 1) T_\Sigma & \text{if} \quad \beta > 3 + 2\sqrt{2} \end{cases}$$

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

$$0 < T_F \ll \min\left(\sqrt{\beta} T_\Sigma,\, \lambda T_\Sigma\right). \tag{26}$$

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

$$\begin{aligned} W_{\text{P\_out}} &= W_{\text{Hum}} W_{\text{F\_out}} W_{\text{Latency}} W_{\text{Inner}} W_{\text{Latency}} \\ &= \frac{k_{\text{P\_out}}}{s(1 + sT_F)(1 + sT_{P2})} e^{-sT_m}, \\ k_{\text{P\_out}} &= k_{\text{P\_Hum}} \omega_{\text{c\_Hum}}, \\ T_m &= T_{\text{Hum}} = 2T_d. \end{aligned} \tag{27}$$

The TF defined in (27) can be used in the design and tuning of the outer loop controller with TF $W_{\text{Contr\_out}}$. The open loop and closed loop TFs, $W_{\text{0\_out}}$ and $W_{\text{C\_out}}$ are:

$$W_{\text{0\_out}} = W_{\text{Contr\_out}} W_{\text{P\_out}} \quad \text{and}$$
$$W_{\text{C\_out}} = \frac{W_{\text{0\_out}}}{1 + W_{\text{0\_out}}}. \tag{28}$$

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

$$W_{\text{P\_out}} \approx \frac{k_{\text{P\_out}}}{s(1 + T_{\text{P\_out}})} e^{-sT_m}, \tag{29}$$

where $T_{\text{P\_out}} = T_F + T_{P2}$. Using Padé approximation the TF of the outer loop process is approximated as:

$$\begin{aligned} &W_{\text{P\_out}} \approx W_{\text{P\_out\_Padé}} \\ &= W_{\text{Hum\_Padé}} W_{\text{F\_out}} W_{\text{Padé}} W_{\text{Inner}} W_{\text{Padé}} \\ &= \frac{k_{\text{P\_out}} (1 - sT_{\text{Hum}}/2)(1 - sT_d/2)^2}{s(1 + sT_F)(1 + sT_{P2})(1 + sT_{\text{Hum}}/2)(1 + sT_d/2)^2}. \end{aligned} \tag{30}$$

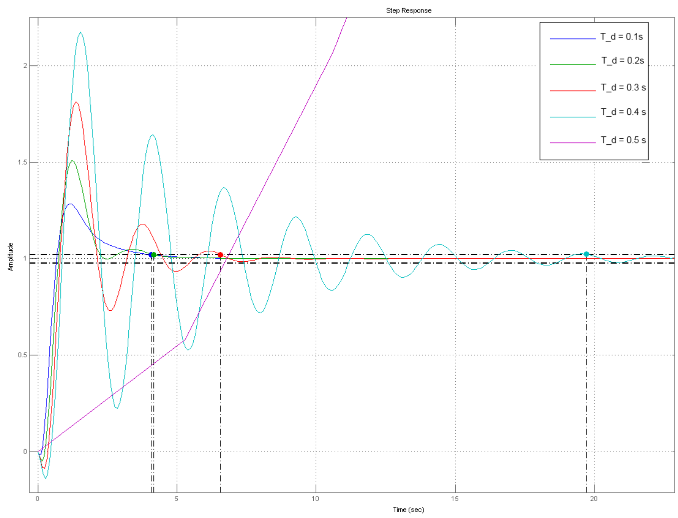

Fig. 2. The robustness of Kessler's method proven through its ability to compensate for latencies up to 0.5 s, originally not incorporated in the system model.

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 straight 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 constraint is compensated, the robustness of the design method can be exploited. Understandably, this will return the same results as the previous (classical) method for $T_d \le 0.0218$, 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. β_{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 β_{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_σ. In this case, applying the previous β 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.

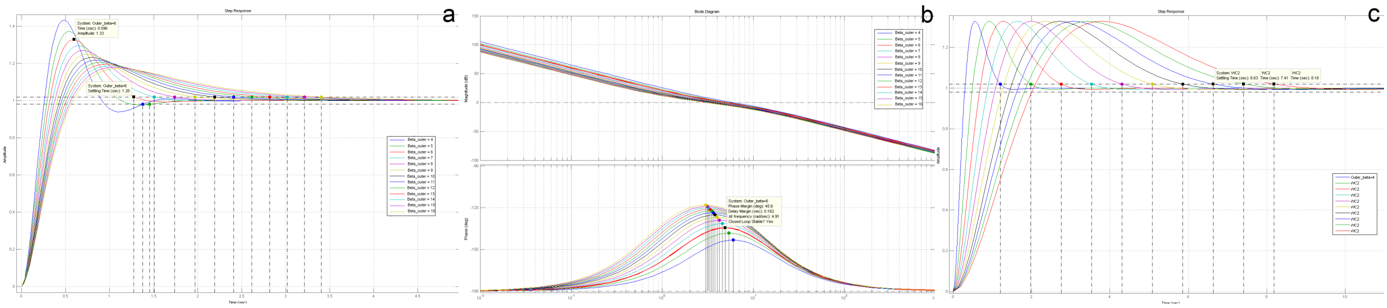

Fig. 1. a) Step response of the whole closed loop system with different β_{Outer} settings employing the stretched version of Kessler's method. T_d was 0.1 s. b) Bode plot of the system with the same settings. c) Step response of the system with $\beta_{\text{Inner}} = \beta_{\text{Outer}} = 6$ and $T_d = 0.1$–1 s.

Table 2. Controller performance parameters with different β_{Outer} settings

β_{Outer}	Phase Margin	Overshoot	Settling time
4	41°	43%	0.57 s
5	41.5°	37%	0.54 s
6	42.3°	33%	0.47 s
7	43.3°	30%	0.61 s
8	44.3°	27%	0.69 s
9	**45.3°**	**25%**	**0.77 s**
10	46.2°	23%	0.84 s
11	47.1°	22%	0.92 s
12	47.9°	21%	0.99 s
13	48.7°	20%	1.06 s
14	49.4°	19%	1.12 s
15	50.1°	18%	1.19 s
16	50.8°	17%	1.26 s

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:

$$W_{\text{C\_out}} = \frac{W_{\text{Contr\_out}} W_{\text{P\_out}}}{1 + W_{\text{Contr\_out}} W_{\text{P\_out}}} e^{-sT_d}. \quad (31)$$

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 5^{th} 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 ($> 5^{\text{th}}$) 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 ($A_{\max}$) 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 ($> 15^{\text{th}}$) order Padé approximation should be used based on Table 3.

Table 3. Effect of the order of Padé approximation on control parameters.

Order of Padé approximation	$A_{\max}$	Overshoot	Settling time
1	95.3%	0%	4.58 s
3	50.6%	2%	3.19 s
5	32.5%	6%	3.04 s
7	25.1%	12%	2.83 s
9	17.4%	17%	2.71 s
11	14.8%	21%	2.64 s
13	12.2%	24%	2.61 s
15	**10%**	**25%**	**2.60 s**
17	8.6%	27%	2.67 s
19	7.2%	27%	2.69 s
21	6.2%	28%	2.71 s

Table 4. Effect of β_{Outer} on control parameters.

β_{Outer}	$A_{\max}$	Overshoot	Settling time
4	18.4%	22%	2.58 s
5	15.7%	25%	2.61 s
6	13.6%	26%	2.62 s
7	12.1%	27%	2.49 s
8	11%	25%	2.54 s
9	**10%**	**25%**	**2.61 s**
10	9.5%	24%	2.79 s
11	8.9%	23%	2.85 s
12	8.5%	22%	2.9 s
13	8%	21%	2.95 s
14	7.7%	20%	3 s
15	7.4%	20%	3.06 s
16	7.1%	19%	3.14 s

Our previous considerations for β are valid here as well, therefore $\beta_{\text{Inner}} = 6$ provides a rational compromise between rise-time and overshoot. With 15^{th} 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 β 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

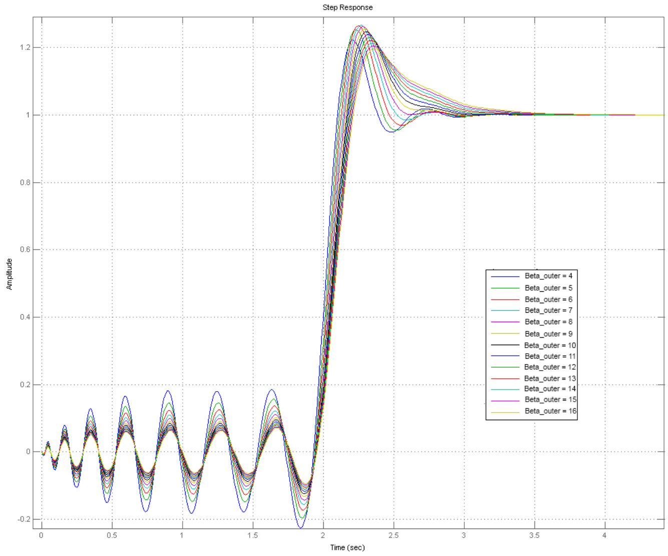

Fig. 3. Kessler's method employed with Smith predictor for large latencies. The β_{Outer} control parameter's effect in the oscillation in the hold phase.

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 serv 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]).

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