# Time Delay Compensation for Networked Control Systems

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**Abstract–The main contribution of this paper is to present a basic direct control telemanipulation simulation that allows the user to control a Spring-Mass-Damper System which act like an object within a virtual world in order to interact with a virtual wall. One of the most important problems of a closed-loop telemanipulation application is the transmission time delay, which can destabilize the system. Furthermore, when using computer network for sending data, time delay is not even constant. This paper also presents a simulation of a force-feedback telemanipulation system for observing and compensating the effect of time delay.**

## I. INTRODUCTION

When telemanipulation is performed over a long distance between the operator site and the remote site such as outer space or undersea, a time delay appears in the information transmission. This time delay can destabilize a bilateral teleoperator system.

The instability caused by time delay has been revealed by Ferrell [1] as early as 1965. Since that, various approaches for handling the problem of time delay [2] have appeared in the literature, like delay modelling and control system design [3], predictive displays and advanced operator interfaces [4], shared compliance control [5], impedance control [6], or supervisory control [7].

Computer Networked Control enables systems to be distributed. The concept of an operator and robot can be replaced with some combination of multiple operators, multiple robots, and maybe even multiple assistant agents that work together in a cooperative environment [8].

## II. SAMPLE VIRTUAL TELEMANIPULATION

The configuration of the Sample Virtual Telemanipulation system can be seen on Fig. 1. The operator gives a position reference to the master device. In this case the master device is just a controller. The slave device is a simple, 1-Degree Of Freedom Spring-Mass-Damper system. Wide variety of dynamics can be represented by changing the parameters, like mass (m), damping coefficient (d) and stiffness (k). A time delay block models the communication network. Two sets of problems can be examined with this configuration:

- ·The variation of time delay in the communication channel. Special prediction method is used to compensate altering time delay.
- ·The variation of the parameters of the Slave Device is another challenge to the controller.

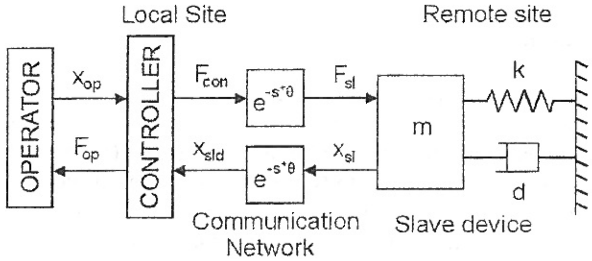


Fig. 1: Configuration of the Sample Telemanipulation

### A. The Slave Device as a 1-DOF Spring-Mass-Damper System

The equation of the Slave Device:

$$m\ddot{x}_{sl} + d\dot{x}_{sl} + kx_{sl} = F_{sl} \tag{1}$$

Applying the Laplace operator on (1):

$$Y_{sl}(s) = \frac{x_{sl}(s)}{F_{sl}(s)} = \frac{1}{ms^2 + ds + k} \tag{2}$$

In this section the solution of (1) is discussed. The charasteristical equation of (1) is:

$$\lambda^2 + \frac{d}{m}\lambda + \frac{k}{m} = 0 \tag{3}$$

where

$$\lambda_{1,2} = \frac{-d \pm \sqrt{d^2 - 4mk}}{2m} \tag{4}$$

The solutions of (4) are divided into thee parts.

First, when $d^2 > 4mk$ in equation (4), (3) has real roots. In this case the solution of (1) is:

$$x_{sl}(t) = c_1 e^{\lambda_1 t} + c_2 e^{\lambda_2 t} \tag{5}$$

where c1 and c2 came from the initial conditions. The equation of the solution does not contain periodic function. This case is called overdamped system in the theory of mechanical vibrations.
The transfer function of this system is:

$$Y_{sl}^{1}(s)=\frac{1}{(s-\lambda_1)(s-\lambda_2)} \qquad (6)$$

In this case the transfer function of the slave device can be coupled into a series of two first-order filters.
Second, when $b^2 = 4mk$ in equation (4), (3) has equal real roots (λ). In this case the solution of (1) is:

$$x_{sl}(t)=c_1 e^{\lambda t}+c_2 t e^{\lambda t} \qquad (7)$$

where $c_1$ and $c_2$ are the same as above. This case is called critically damped solution. This is important in the application of the theory of mechanical vibrations. In this case the system reaches the steady state in minimal time. This case has been applied in the controller as a reference system.
The transfer function of the Slave Device (2) can be transformed into the following form:

$$Y_{sl}^{2}(s)=\frac{1}{(s-\lambda)^2} \qquad (8)$$

which is a second-order filter.
Third, when $b^2 < 4mk$ in equation (4), (3) has complex roots, like $\lambda_1 = a+ib$ and $\lambda_2 = a-ib$ . Then the solution of (1) is:

$$x_{sl}(t)=e^{at}(c_1\cos(bx)+c_2\sin(bx)) \qquad (9)$$

where $c_1$ and $c_2$ are the same as in the first case. This case is called underdamped solution.
Every setting of the parameters of the Slave Device fits in one of the above-mentioned three possible solutions. The best of these three types of solution is the second but it is hard to realize in real systems.
The controller is chosen in the following way:

$$C_0=\frac{K}{s}Y_{sl}^{-1}(s) \qquad (10)$$

Considering the (2) form of the slave device, the $C_0$ controller is:

$$C_0=\frac{K}{s}\left[ms^2+ds+k\right]=Kd+k\frac{K}{s}+Kms \qquad (11)$$

The (11) form of the controller is a simple PID controller. The terms of (11) are the proportional, integral and differential parts. K is still a free parameter.

B. Simulation without Time Delay Compensation

In this section a simulation of a basic control scheme is introduced as a simple case. In this configuration, Fig. 2, the Master device is a PID controller. The operator gives the reference position to the controller, and the controller controls the master device via the time delayed

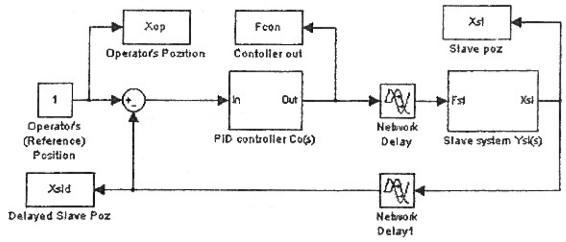


Fig. 2: Position control without time delay compensation

communication network. The force sensing could come from the output of the PI controller to the Operator. This is a local force-feedback case. The Slave Device is an overdamped system.
The controller is defined by (10). The transfer function of the system is:

$$G_{ry}(s)=\frac{x_{sld}(s)}{x_{op}(s)}=\frac{C_0(s)Y_{sl}(s)e^{-2\theta s}}{1+C_0(s)Y_{sl}(s)e^{-2\theta s}}=\frac{\frac{K}{s}e^{-2\theta s}}{1+\frac{K}{s}e^{-2\theta s}} \qquad (12)$$

(12) contains $e^{-2\theta s}$, hence it is a transcendental equation in s, which means that (12) has infinite poles and zeros.
The first simulation stage is the tuning of the controller is $C_0(s)$. There is only one free parameter, K, in (10).
To choose the best value for K, the following criteria is defined:

$$Q_{abs}=\int_{t_0=0}^{t_1=20}\left|x_{op}(s)-x_{sld}(s)\right|dt\approx\sum_{i=1}^{2001}\left|1-x_{sld}(i)\right|*\Delta t \qquad (13)$$

In this simulation the integral is approximated by a sum, because $x_{sld}$ is a column vector, similarly to the output of the simulation. Δt is the time step of the simulation. (13) is dependent only on K in this simulation.

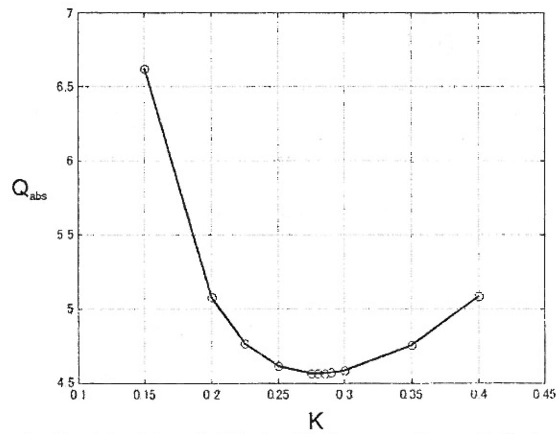


Fig. 3: Absolute Integral Criteria ($Q_{abs}$) versus the controller's free parameter (K)

The variation of Absolute Integral Criteria versus the controller's free parameter (K) can be seen on Fig. 3. This function has a global minimum between K=0.25,0.3. K=0.2 is chosen for the next simulation. The K=0.2 case doesn't have such good Criteria value, but it is more robust against the changing of the time delay.

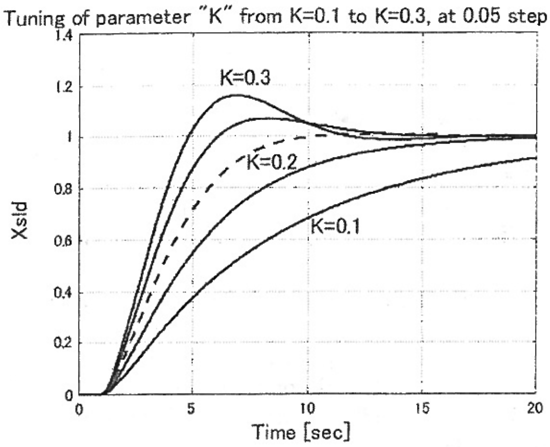


Fig. 4: Tuning of parameter K

The answer of the Slave Device can be seen on Fig. 4. The input was a unity step function. The dashed line is the border between the over- and underdamped case. If K is bigger than 0.2, the system is overshot, and if K is smaller than 0.2, the system becomes an underdamped system.

Fig. 5 shows the simulation result when time delay is alternating. The dashed line shows the delayed position of the Slave Device when the time delay of the network (q) is equal to unity. If the time delay on the network is smaller than the default value in the Smith Predictor, the system gives an underdamped answer to the unity step input from the operator.

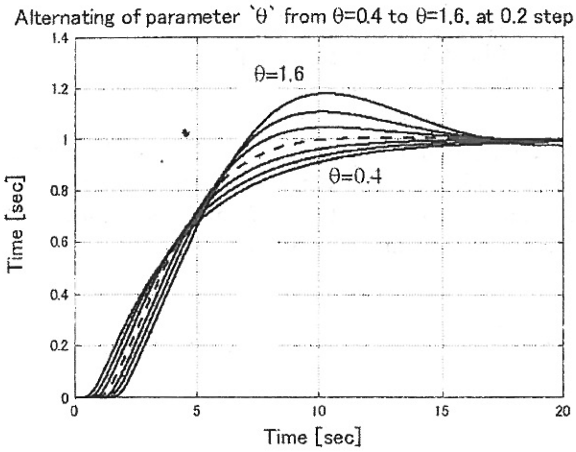


Fig. 5: Alternating of the time delay on the communication network

III. TIME DELAY COMPENSATED SAMPLE VIRTUAL TELEMANIPULATION

A. The Smith Predictor

The Smith Predictor is a classical configuration for time delay compensation Fig. 6. There are two loops in Fig. 7. The minor loop contains a compensation (signal v) that is added to the error signal. In this configuration, equation of the controller is defined by (11). The $P_0(s)$ is the model of the P(s) plant. $P_0(s)$ is the critically damped case (8) of the Slave Device.

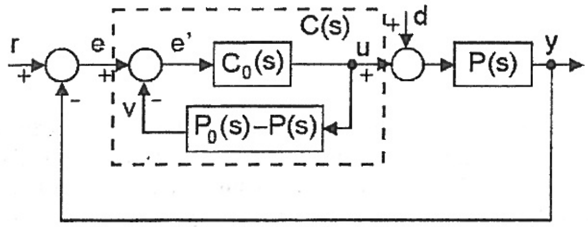


Fig. 6: The Configuration of the Smith Predictor

B. Simulation with static time delay, tuning of K

Fig. 7. shows the simulation setup. The Absolute Integral Criteria versus free control parameter can seen in Fig. 8. It seems that this function does not have a global minimum. It will be proofed later. K can be chosen much greater than in the non-compensated case, but the robustness against the time delay uncertainty will be lost. This came from the simulation results so K is chosen to 0.7.

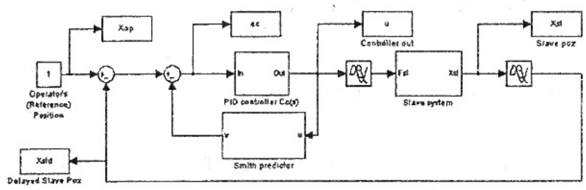


Fig. 7: Simulation setup

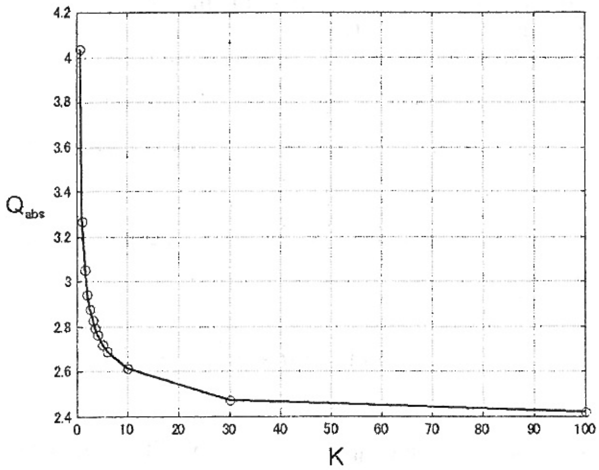


Fig. 8: Absolute Integral Criteria ($Q_{abs}$) versus controller's free parameter (K)

The answer of the Slave Device can be seen in Fig 9. The input was a unity step function. The dashed line is the border between the over- and underdamped case. If K is greater than 0.7, the system is overshot, and if K is smaller than 0.7, the system become an underdamped system. Compared to the non-compensated case, K can be higher. This means that the compensated control loop has better dynamics.

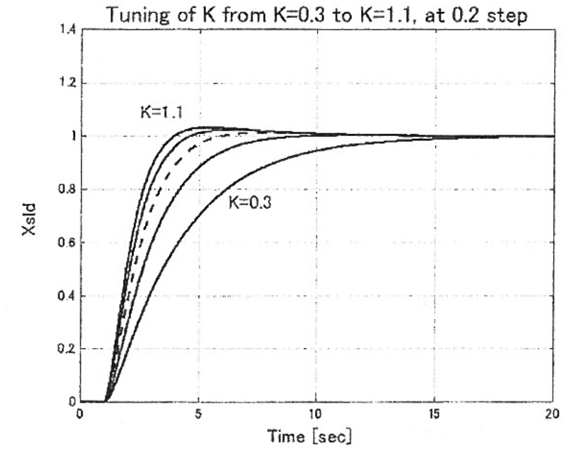


Fig. 9. Tuning of parameter K

C. Simulation with static K and variable time delay

The difference between the non-compensated and compensated systems is the robustness against time delay changing. Fig. 10 compared to Fig. 9, rising time is shorter, which means a better dynamic performance.

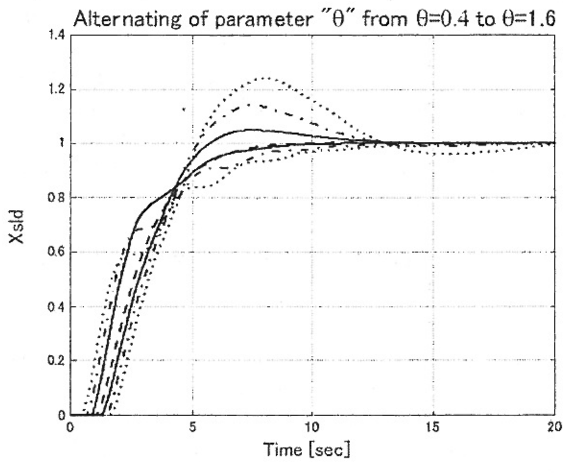


Fig. 10: Alternating of the time delay on the communication network

## 4. CONCLUSION

Computer Network Controlled Systems have become more important in modern technology recently. One of the biggest problems of a computer network is transmission time delay. The main contribution of this paper was to present a basic control scheme to simulate a Spring-Mass-Damper (SMD) System. A Smith Predictor compensator for eliminating network time delay was also presented. Compensated and non-compensated systems were compared: the compensated system had a better dynamic performance than the non-compensated one.

## IV. REFERENCES


[1] W. R. FERRELL: Remote Manipulation with Transmission Delay. IEEE Transactions on Human Factors in Electronics, pp. 24-32, 1965

[2] Ren C. LUO, Tse Min CHEN, Chih-Chen YIN: Intelligent Autonomous Mobile Robot Control through the Internet. ISIE 2000, Cholula, Puebla, Mexico, 2000

[3] Sukhan LEE, Hahk Sung LEE: Advanced Telemanipulation under Time-delay. SPIE OE/Technology '92: Telemanipulator Technology, 1992

[4] A. K. BEJCZY, W. S. KIM, S. C. VENEMA: The Phantom Robot: Predictive Displays for Teleoperations with Time-delays. IEEE International Conference on Robotics and Automation, pp. 546-551, 1990

[5] Won S. KIM, Blake HANNAFORD, Antal K. BEJCZY: Force-reflection and Shared Compliant Control in Operating Telemanipulators with Time-delay. IEEE Transactions on Robotics and Automation, pp. 176-185, 1992

[6] Paul G. BACKES: Multi-sensor Based Impedance Control for Task Execution. IEEE International Conference on Robotics and Automation, pp. 1245-1250, 1992

[7] W. R. FERRELL, T. B. SHARIDAN: Supervisory Control of Remote Manipulation. IEEE Spectrum, pp. 81-88, 1967

[8] Barney DALTON, Ken TAYLOR: A Framework for Internet Robotics. Proceedings of IEEE/RSJ Int. Conf. on Intelligent Robots and Systems, WS2, pp. 15-22, 1998

[9] Smith O. J. M.: A Controller to Overcome Dead Time. Chem. Eng. Prog. 53, 217, 1959

[10]Suradech MANOROTKUL: Tele-handshaking through the Internet. Master Thesis, Department of Electrical Engineering, Faculty of Engineering, Institute of Industrial Science, University of Tokyo, 1996