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QOS BASED CONTROL OF TELEOPERATION VIA INTERNET

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Abstract: This paper presents an QoS (quality of service) based control system of teleoperation via the Internet. Quality of service on the Internet refers to a set of quality requirements on the performance of the data transmission necessary to achieve the required functionality of an application. The quality of data transmission via the Internet is measured or reflected by a set of QoS parameters. Since the stability of the teleoperation system is sensitive to the data transmission quality of the Internet, it is important to adjust the control strategy of robot systems in teleoperation based on the quality (reflected by measured QoS parameters) of the network for data transmission. One of the widely used QoS parameters is network delay. This paper proposes a robot controller gains adjustment scheme based on QoS parameters (network delay) measured using a quadratic programming approach. Moreover, a teleoperation experiment is presented to demonstrate the effectiveness of the proposed controller gains adjustment scheme.

Keywords: Quality of Service, Teleoperation, Round-trip Time, Quadratic Programming

1. INTRODUCTION

A teleoperation system is a system that involves interaction between human operators and remote robotic systems via communication channels. With the help of the development of the Internet, telerobotic systems can be built on the Internet, instead of dedicated communication channels, so that the concept of “E-services” can be realized by operating robotic systems in remote sites to provide various kind of services, like tele-medicine and tele-manufacturing. However, the quality of the services provided by the technology of teleoperation via the Internet cannot be guaranteed. This paper is to study the quality of service issue of teleoperation systems and how to maintain the system performance when the communication performance of the Internet is poor.

The concept of Quality of Service (QoS) is first introduced in computer network area and is widely discussed in distributed multimedia applications. QoS is defined as a set of quality requirements on the performance of the data transmission necessary to achieve the required functionality of an application. The quality of data transmission via the Internet is reflected by a set of QoS parameters. This paper studies how to adjust robot control strategies based on the measured QoS parameters so as to achieve good performance and maintain stability when the quality of the Internet for communication is not good. A quadratic programming based approach is proposed to adjust controller gains based on the QoS parameters measured.

Few works have been conducted to investigate the QoS issues in teleoperation control. Nahrstedt and Smith employed the QoS Broker for network resource management (e.g. bandwidth allocation for video transmission) for a teleoperation system (Nahrstedt and Smith, 1994). Only ad-hoc heuristics were devised in the QoS Broker for network resource management and no mathematical analysis on the performance of

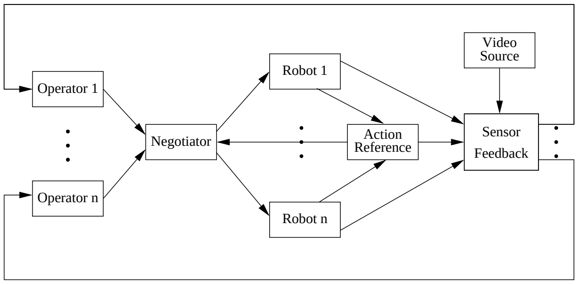


Fig. 1. The teleoperation system framework.

the QoS Broker was included. Moreover, the stability issue of the telerobotic system, which is an important issue in control systems design, was also not considered. On the other hand, Wang *et. al.* proposed a fuzzy inference approach to generate a QoS index from QoS parameters for adjusting the frame rate of online video feedback in a teleoperation system (Wang *et al.*, 2001). The generated QoS index, however, is difficult to be incorporated in robot system models for analysis. Only heuristics can be devised for control strategy adjustment based on this QoS index.

2. QOS BASED CONTROL FOR TELEOPERATION

This section describes a QoS based control approach for teleoperation. The concept of QoS (Quality of Service) is briefly introduced in this section. A QoS based multi-operators multi-robots teleoperation framework is also presented.

2.1 QoS Parameters

The quality of service of a teleoperation system is reflected by a set of QoS parameters measured that indicates the characteristics of the operating environment of the system. The operating environment characteristics of a teleoperation system refer to the quality of data transmission in the Internet and the computational and memory resource allocation in the computers for robot control. For the measurement of the quality of data transmission via the Internet, a set of QoS parameters, including network delay, delay jitter, bandwidth allocated, packet loss rate, etc., are employed. On the other hand, QoS parameters related to robot control computation include CPU time and memory allocated for controller computation and so on. The effect of computer network related QoS parameters dominates in teleoperation systems as the performance of the communication channels (the Internet) plays an important role in the stability of the teleoperation systems. One of the most widely studied network related QoS parameter is network delay and this paper studies the role of network delay in the proposed teleoperation framework.

The measurement of QoS parameters for teleoperation systems may sometimes be difficult because real-time measurement is required for collecting the on-time and accurate picture of the status of the operating environment. For instance, small probe packets are required to be sent periodically from one node to other nodes in the network for the measurement of network delay. Moreover, accurate clock synchronization (Arvind, 1994) among nodes over the network is necessary for accurate network delay measurement. However, the accuracy provided by existing clock synchronization algorithms is not acceptable for network delay measurement. Therefore, round-trip delay is usually employed for network delay measurement because clock synchronization among nodes on the network is not required.

2.2 QoS based Framework

Fig 1 depicts a multi-operators multi-robots teleoperation framework. In the proposed framework, each operator can be anywhere in the world that has Internet access and has a force feedback joystick setup in his/her side to control robot in remote site. Each operator is responsible for controlling a robot in remote site with the help of online video feedback and force fed-back from the robot. Each robot is equipped with a local controller that accept operator's command as input. Sensor data is gathered from the robots and is sent to local robot controllers. Moreover, based on the QoS parameters (network delay) measured, a controller gain adjustment scheme is developed (see Section 3) to maintain the system stability in spite of the network delay in the system.

All operator commands are first sent to the Negotiator which serves two functions in teleoperation. The first function of the Negotiator is to coordinate joystick command from each operator and motion of each robot when conflicting commands are given to the robots. The Negotiator is equipped with an online command learner to capture the intention of each operator based on the past commands given to the robots. When the network status is in poor quality (reflected by QoS parameters measured), the confidence of the Negotiator on received operators' commands drops and the Negotiator tries to predict what the actual operator commands are. The second function of the Negotiator is to fuse predicted commands with operator commands based on the measured QoS parameters so as to improve the efficiency of the teleoperation system. The Negotiator then outputs reference velocity commands to each local robot controller.

3. CONTROLLER GAINS ADJUSTMENT

The QoS parameter employed in robot controller gains adjustment in teleoperation is the time delay involved in information transmission via the Internet. Time delay is introduced into the model of the robot control system. The introduction of the controller gains adjustment scheme is to make the teleoperation system stable under the influence of network delay. In this paper, we take the control of a robot manipulator as an example to study the proposed controller gains adjustment scheme based on measured QoS parameters (network delay).

3.1 *Robot Manipulator Control*

The dynamic model of a robot manipulator with six degrees of freedom (DOF) is given by,

$$\begin{cases} \mathbf{D}(q)\ddot{q} + \mathbf{C}(q,\dot{q}) + \mathbf{G}(q) = \tau \\ Y = \mathbf{h}(q) \end{cases} \tag{1}$$

where q is the joint angle vector, τ is the joint torque vector, $Y = [x, y, z, O, A, T]$ is the robot position and orientation output, $\mathbf{D}(q)$ is the inertia matrix, $\mathbf{C}(q, \dot{q})$ is the centripetal and coriolis terms, $\mathbf{G}(q)$ is the gravity term and $q, \tau, Y \in \mathbb{R}^6$. Nonlinear feedback control (Tarn *et al.*, 1984) technique is employed to linearize and decouple the dynamic model (1) and convert the nonlinear control problem to a linear control problem.

The robot dynamic model can be rewritten in a standard nonlinear state space form by letting $\omega_1 = q$, $\omega_2 = \dot{q}$, $\omega = [\omega_1, \omega_2]^{\mathrm{T}}$ and $\mathbf{E}(\omega_1, \omega_2) = \mathbf{C}(\omega_1, \omega_2) + \mathbf{G}(\omega_1)$,

$$\begin{cases} \dot{\omega} = \underbrace{\begin{bmatrix} \omega_2 \\ -\mathbf{D}^{-1}(\omega_1)\mathbf{E}(\omega_1) \end{bmatrix}}_{\mathbf{f}(\omega)} + \underbrace{\begin{bmatrix} 0 \\ \mathbf{D}^{-1}(\omega_1) \end{bmatrix}}_{\mathbf{g}(\omega)} \tau \\ Y = \mathbf{h}(\omega_1) \end{cases} \tag{2}$$

Based on the differential geometric control theory (Isidori, 1989), there exists a diffeomorphic state transformation $T(\omega)$ and a nonlinear feedback law that linearizes and decouples the robot dynamics. The diffeomorphic state transformation $T(\omega)$ is given by $T(\omega) = [h_1(\omega_1), L_f h_1(\omega_1), \cdots, h_6(\omega_1), L_f h_6(\omega_1)]$ and the nonlinear feedback law is $\tau = \alpha(\omega) + \beta(\omega)v$ with

$$\begin{cases} \alpha(\omega) = -\mathbf{D}(\omega_1)\mathbf{J}_h^{-1}\left(\dot{\mathbf{J}}_h\dot{q} - \mathbf{J}_h\mathbf{D}^{-1}(\omega_1)\mathbf{E}(\omega)\right) \\ \beta(\omega) = \mathbf{D}(\omega_1)\mathbf{J}_h^{-1} \end{cases} \tag{3}$$

where h_i is the i-th component of $\mathbf{h}(q)$, L_f^k denotes the k-th Lie derivative of $\mathbf{h}(\omega)$ along the vector field $\mathbf{f}(\omega)$ and $\mathbf{J}_h$ is the output Jacobian matrix of $\mathbf{h}(\omega_1)$.

In the transformed state $T(\omega)$ with the auxiliary input v, the dynamic model (2) is in the Brunowsky canonical form and can be decomposed into six linear decoupled subsystems

$$\begin{cases} \dot{\Theta}_i = \underbrace{\begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}}_{\mathbf{A}} \Theta_i + \underbrace{\begin{bmatrix} 0 \\ 1 \end{bmatrix}}_{\mathbf{B}} v_i \\ y_i = \begin{bmatrix} 1 & 0 \end{bmatrix} \Theta_i \end{cases} \tag{4}$$

where $\Theta_i = [h_i, L_f h_i]^{\mathrm{T}}$, $i = 1, \ldots, 6$. The model (4) represents the behavior of the system in the k-th time interval $t \in [kT + \tau_k, (k+1)T + \tau_{k+1})$ in a teleoperation system that has non-deterministic time delay τ_k inherited in information transmission via the Internet. Note that each identical subsystem has double poles at the origin and thus is not asymptotically stable.

Assume that the time delay τ_k is less than one sampling period T, $\tau_k < T, \forall k$. By sampling the system, the time-delayed discrete-time model is given as follows (Åström and Wittenmark, 1997),

$$\begin{aligned} \Theta_i(kT + T) = {} & \Phi\Theta_i(kT) + \Gamma_0(\tau_k)v(kT) \\ & + \Gamma_1(\tau_k)v(kT - T) \end{aligned} \tag{5}$$

where

$$\begin{aligned} \Phi &= \exp(\mathbf{A}T) = \begin{bmatrix} 1 & T \\ 0 & 1 \end{bmatrix} \\ \Gamma_0(\tau_k) &= \int_0^{T-\tau_k} \exp(\mathbf{A}t)\mathbf{B}dt = \begin{bmatrix} \frac{1}{2}(T - \tau_k)^2 \\ T - \tau_k \end{bmatrix} \\ \Gamma_1(\tau_k) &= \int_{T-\tau_k}^{T} \exp(\mathbf{A}t)\mathbf{B}dt = \begin{bmatrix} \tau_k(T - \frac{\tau_k}{2}) \\ \tau_k \end{bmatrix} \end{aligned} \tag{6}$$

By introducing the PD feedback control law $v_i(t^+) = v_i^*(t) - \mathbf{F}_i\Theta_i(t - \tau_k)$, $i = 1, \ldots, 6$, where $\mathbf{F}_i = [f_{i_1}, f_{i_2}]$ and $v_i(t^+)$ is piecewise continuous and only changes value at $(kT + \tau_k)$, the closed loop subsystem is given as,

$$\xi_i(kT + T) = \tilde{\mathbf{A}}\xi_i(kT) + \tilde{\mathbf{B}}v_i^*(kT) \tag{7}$$

where ξ_i is the augmented state vector defined as

$$\begin{aligned} \xi_i(kT) &= \begin{bmatrix} \Theta_i(kT) \\ \Theta_i(kT - T) \\ v_i^*(kT - T) \end{bmatrix} \quad \text{and} \quad \tilde{\mathbf{B}} = \begin{bmatrix} \Gamma_0(\tau_k) \\ 0 \\ \mathbf{I} \end{bmatrix} \\ \tilde{\mathbf{A}} &= \begin{bmatrix} (\Phi - \Gamma_0(\tau_k)\mathbf{F}_i) & -\Gamma_1(\tau_k)\mathbf{F}_i & \Gamma_1(\tau_k) \\ \mathbf{I} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \end{aligned} \tag{8}$$

When the network delay is longer than one sampling period $((\lambda - 1)T < \tau_k < \lambda T, \lambda > 1)$, the delay can be written as $\tau_k = (\lambda - 1)T + \tau_k'$ where $0 < \tau_k' < T$. The augmented system (7) is then modified as follows (Åström and Wittenmark, 1997),

$$\begin{aligned} \xi_i(kT) &= \left[\begin{array}{c} \Theta_i(kT) \\ \Theta_i(kT - T) \\ \vdots \\ \Theta_i(kT - (\lambda - 1)T) \\ \hline \Theta_i(kT - \lambda T) \\ v^*(kT - \lambda T) \\ \hline v^*(kT - (\lambda - 1)T) \\ \vdots \\ v_i^*(kT - 2T) \\ v_i^*(kT - T) \end{array}\right] \quad \text{and} \quad \tilde{\mathbf{B}} = \left[\begin{array}{c} 0 \\ \vdots \\ 0 \\ \hline 0 \\ \hline 0 \\ \hline 0 \\ \vdots \\ 0 \\ \mathbf{I} \end{array}\right] \\ \tilde{\mathbf{A}} &= \left[\begin{array}{c|c|c} \tilde{\mathbf{A}}_{11} & \tilde{\mathbf{A}}_{12} & \tilde{\mathbf{A}}_{13} \\ \hline \mathbf{I} & 0 & 0 \\ 0 & 0 & \mathbf{I} \\ \hline 0 & 0 & 0 \end{array}\right] \end{aligned} \tag{9}$$

where

$$\tilde{\mathbf{A}}_{11} = \left[\, \Phi \;\; 0 \;\; \cdots \;\; 0 \;\; -\Gamma_0(\tau_k')\mathbf{F}_i \,\right]$$
$$\tilde{\mathbf{A}}_{12} = \left[\, -\Gamma_1(\tau_k')\mathbf{F}_i \;\; \Gamma_1(\tau_k') \,\right]$$
$$\tilde{\mathbf{A}}_{13} = \left[\, \Gamma_0(\tau_k') \;\; 0 \;\; \cdots \;\; 0 \,\right]$$

In order to study the stability condition of the robot system for controller gain $\mathbf{F}_i$ adjustment scheme derivation, Jury's test (Franklin *et al.*, 1990) is applied on the characteristic equation of (7). By considering the positivity of the odd entries in the first column of the Jury array, the stability conditions for the controller gain $\mathbf{F}_i$ of the subsystem i is given as follows,

$$\begin{aligned} 1 - \left(\frac{1}{2} f_{i_1}\tau_k^2 - f_{i_2}\tau_k\right)^2 &> 0 \\ a(f_{i_1}, f_{i_2})b(f_{i_1}, f_{i_2}) &> 0 \\ f_{i_1}\left[f_{i_2}(T - 2\tau_k) - f_{i_1}\tau_k(T - \tau_k) - 2\right] &< 0 \end{aligned}$$

where

$$\begin{aligned} a(f_{i_1}, f_{i_2}) = {} & -\tau_k^2(T - 2\tau_k)f_{i_1}^2 + 4\tau_k f_{i_2}^2 \\ & +2\tau_k(T - 3\tau_k)f_{i_1}f_{i_2} + 2(T + 2\tau_k)f_{i_1} \\ & -4f_{i_2} \\ b(f_{i_1}, f_{i_2}) = {} & \tau_k^2(T^2 - 2T\tau_k + 2\tau_k^2)f_{i_1}^2 \\ & +4\tau_k(2\tau_k - T)f_{i_2}^2 \\ & +2\tau_k(3T\tau_k - 4\tau_k^2 - T^2)f_{i_1}f_{i_2} \\ & -2T(T + 2\tau_k)f_{i_1} + 4Tf_{i_2} - 8 \end{aligned}$$

The above-mentioned conditions are also suitable for system with network delays longer than one sampling period ($\tau_k > T$) with τ_k substituted by $\tau_k' = \tau_k - (\lambda - 1)T$, where $(\lambda - 1)T < \tau_k < \lambda T$ and $\lambda > 1$. It is worth to be noted that the conditions depend on QoS parameters (network delay τ_k), sampling period T and controller gains (f_{i_1}, f_{i_2}). If only positive gains $(f_{i_1}, f_{i_2} > 0)$ are considered, we have

$$\mathcal{C} : \begin{cases} \frac{1}{2}\tau_k f_{i_1} - \frac{1}{\tau_k} < f_{i_2} < \frac{1}{2}\tau_k f_{i_1} + \frac{1}{\tau_k} \\ a(f_{i_1}, f_{i_2})b(f_{i_1}, f_{i_2}) > 0 \\ 0 < f_{i_2} < \dfrac{f_{i_1}\tau_k(T - \tau_k) + 2}{T - 2\tau_k} \end{cases} \qquad (10)$$

It can be easily showed that $a(f_{i_1}, f_{i_2}) = 0$ and $b(f_{i_1}, f_{i_2}) = 0$ represent hyperbolic boundaries in the $f_{i_1} - f_{i_2}$ gain plane (Zwillinger, 1996). If a particular pair of controller gains (f_{i_1}', f_{i_2}') satisfies condition $\mathcal{C}$, the system is stable. Otherwise, a quadratic programming problem is formulated to adjust the controller gains so as to bring the system back to the stable state.

3.2 Gain Adjustment Scheme

The basic concept of controller gain adjustment scheme is described as follows. Assume that a pair of nominal gains $(\overline{f_{i_1}}, \overline{f_{i_2}})$ is assigned to the robot subsystem i. The nominal gains are the controller gains designed for the system under scenarios that do not have time delays. The nominal gains are, at the same time, designed to satisfy certain performance requirements of the system. The current employed controller gains (f_{i_1}, f_{i_2}) are examined to see whether the robot subsystem lies outside the derived stability region defined by conditions $\mathcal{C}$. If the system lies within the stable region with the current controller gains, the current gains are kept using in the robot system, else the nominal gains $(\overline{f_{i_1}}, \overline{f_{i_2}})$ are examined to see whether the system lies within stable region with the nominal gains. If the system lies within the stable region with the nominal gains $(\overline{f_{i_1}}, \overline{f_{i_2}})$ based on the measured QoS parameter (network delay τ_k), the controller gains are then set to the nominal gains, else a controller gains pair $(\hat{f_{i_1}}, \hat{f_{i_2}})$ is selected for the system so that it is within the stable region and the distance between it and the nominal gains is minimized.

A quadratic programming (QP) problem is formulated to approximate the controller gain $(\hat{f_{i_1}}, \hat{f_{i_2}})$ selection process. The quadratic program helps to determine a controller gains pair $(\hat{f_{i_1}}, \hat{f_{i_2}})$ that is nearest to the nominal gains $(\overline{f_{i_1}}, \overline{f_{i_2}})$ pair in the $f_{i_1} - f_{i_2}$ plane and lies within the stable region defined by conditions $\mathcal{C}$. The objective function of the optimization problem is thus constructed by the Euclidean distance between the nominal gains and any gains pair or

$$d(f_{i_1}, f_{i_2}) = (f_{i_1} - \overline{f_{i_1}})^2 + (f_{i_2} - \overline{f_{i_2}})^2$$

The constraint set of the optimization problem, on the other hand, is constructed from the conditions $\mathcal{C}$, which consists of linear constraints, except the second conditions $a(f_{i_1}, f_{i_2})b(f_{i_1}, f_{i_2}) > 0$. As discussed in previous section, both $a(f_{i_1}, f_{i_2}) = 0$ and $b(f_{i_1}, f_{i_2}) = 0$ represent hyperbolic boundaries on the $f_{i_1} - f_{i_2}$ plane. Each hyperbolic boundary is approximated by three linear boundaries with two of them come from the asymptotes of the hyperbola and the remaining one comes from a line that is perpendicular to the major axis of the hyperbola and passes through the focus, as shown in Fig 2. After the approximation, all stability conditions described in $\mathcal{C}$ are linear. Therefore, a quadratic program can be constructed to adjust controller gains for the robot system. The quadratic program is expressed as follows,

$$\begin{aligned} \min \quad & \frac{1}{2}\left[\, f_{i_1} \;\; f_{i_2} \,\right]\begin{bmatrix} 2 & 0 \\ 0 & 2 \end{bmatrix}\begin{bmatrix} f_{i_1} \\ f_{i_2} \end{bmatrix} - 2\left[\, \overline{f_{i_1}} \;\; \overline{f_{i_2}} \,\right]\begin{bmatrix} f_{i_1} \\ f_{i_2} \end{bmatrix} \\ \text{st.} \quad & \mathbf{A}_{\mathcal{C}}\begin{bmatrix} f_{i_1} \\ f_{i_2} \end{bmatrix} \le \mathbf{b}_{\mathcal{C}}, \qquad f_{i_1} > 0,\; f_{i_2} > 0 \end{aligned}$$

where $\mathbf{A}_{\mathcal{C}}$ and $\mathbf{b}_{\mathcal{C}}$ are coefficient matrices of the linear constraints derived from conditions $\mathcal{C}$. Since quadratic programming problem is a well studied optimization problem, many efficient algorithms for solving quadratic programs can be employed for this controller gain adjustment problem (Gill *et al.*, 1981).

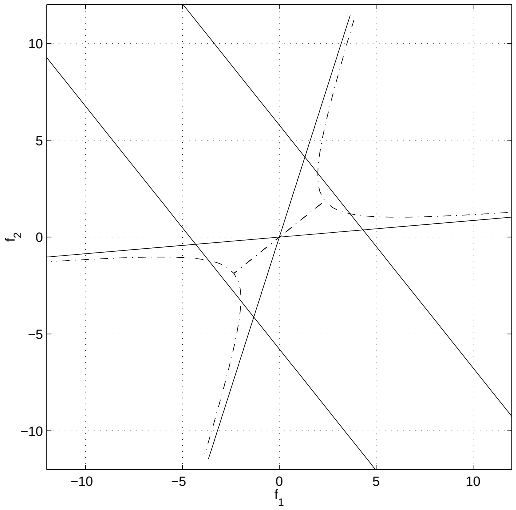


Fig. 2. Approximation of hyperbolic boundaries.

Fig. 3. Pick-and-place experimental setup.

4. EXPERIMENTAL RESULTS

This section describes a teleoperation experiment that connects a mobile manipulator (of Robotics and Automation Laboratory, Michigan State University) and a human operator (of Robot Control Laboratory, The Chinese University of Hong Kong) by the Internet. The mobile manipulator consists of a PUMA 560 on top of a Nomadic XR4000 mobile robot. In the experiment, the operator in Hong Kong was asked to control the mobile manipulator via a joystick with force feedback enabled to pick and place three metal pieces on a platform, with the help of video feedback from the remote robot side for operator guidance. The experimental setup is depicted in Fig 3. The Hong Kong operator was asked to pick up the metal pieces and move it forward for 15cm (up to the mark of the pencil shown in Fig 3). This task was performed with and without the proposed QoS based controller gain adjustment scheme applied on robot controllers. Interested readers may refer to (Elhajj *et al.*, 2000) for the implementation details and setup of the system employed in the experiment.

The QoS parameter considered in the experiment is network delay. The round-trip network delay experienced between US and Hong Kong during the experiment has average of 276.5ms and standard deviation of 19.7ms. Round-trip delay, which is assumed to be twice of one-way network delay, is employed for QoS parameter measurement due to its simple implementation. To measure the QoS parameter during the experiment, an one-byte probe signal is sent from the robot server (Robot) to joystick client (Operator) every second and an one-byte acknowledgement signal is sent immediately back to the robot once the joystick client receive the probe signal, as shown in Fig 4. The round-trip delay is then computed at the robot server by taking the time elapsed between the event of sending probe signal and receiving the acknowledgement signal. Fig 5 depicts part of the round-trip delay trace during experiment.

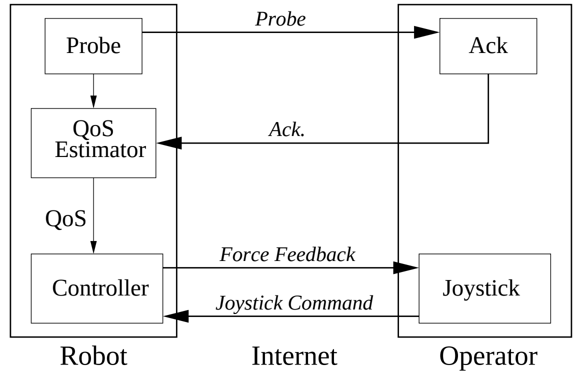


Fig. 4. Measuring QoS parameter (round-trip delay).

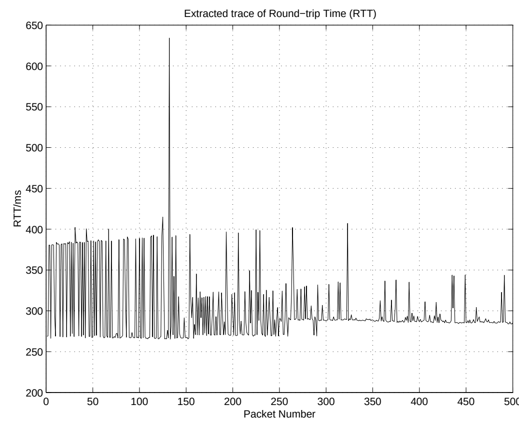
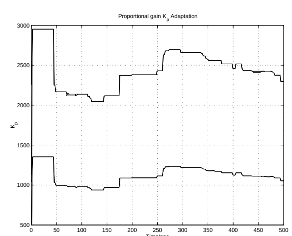


Fig. 5. Extracted trace of network round-trip delay during experiment.



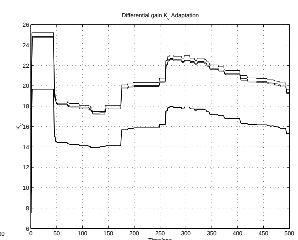


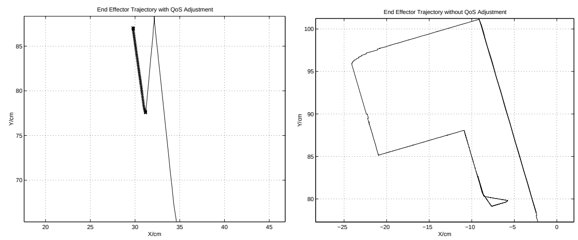
Fig. 6. QoS based proportional gain K_p adaptation.

Fig. 7. QoS based differential gain K_v adaptation.

The main difficulty of the teleoperated pick-and-place task is the correct positioning of the robot gripper

	Task Completion Time (in sec)	
	w/o QoS Gain Adj.	w/ QoS Gain Adj.
Piece L	243	112
Piece M	282	76
Piece R	331	93
Average	285.3	93.7

Table 1. Task completion times.



(a) With QoS Gain Adjustment

(b) Without QoS Gain Adjustment

Fig. 8. Trajectory portions traversed by the gripper.

for grabbing the metal pieces provided with single view of video feedback and indeterministic network quality. The system is sampled at 10Hz. During the experiment, the Hong Kong operator can accomplish the requested pick-and-place task successfully and promptly with QoS based controller gain adjustment, in spite of large network delay. Figs 6 and 7 show the QoS based gains adaptation of robot controllers during experiment. The portion of gripper trajectory, that one of the metal pieces was successfully grabbed and moved, is shown in Fig 8(a). The pick-and-place motion is depicted in the thick trajectory portion while the remaining portion represents gripper positioning motion. On the other hand, the Hong Kong operator, in general, took longer time to position the gripper for grabbing one of the metal pieces and achieve the pick-and-place task without the proposed QoS based controller gain adjustment, as depicted in Fig 8(b). Moreover, the remote operator controlled the gripper to traverse unnecessary paths in order to position it to his desired positions, which contributed to the long task completion time. Table 1 lists the completion time of the assigned pick-and-place task for the Left, Middle and Right metal pieces (L, M and R) with and without QoS based gain adjustment (Fig 3). The average task completion times for the cases with and without the QoS based controller gain adjustment are 93.7s and 285.3s respectively. In additions, the proposed controller gain adjustment scheme guarantee the robot system to have closed loop poles placed in the stable region during the experiment. The remote operator did not lose control on the robot arm in achieving the requested tasks. The mobile manipulator also exhibits motions with fast response to operator commands and small overshoot because the adjusted controller gains are selected to be as similar to the nominal gain as possible, which contributes to the good performance of the system without network delay.

5. CONCLUDING REMARKS

This paper has presented a QoS based control system for teleoperation systems via the Internet. Measured QoS parameters reflect the environmental resource allocation status in which the robots are situated. For teleoperation via the Internet, the QoS parameters involved mainly measure the quality of data transmission through the Internet. Under the proposed QoS based control system, robot controller gains are adjusted based on QoS parameter (network delay) measured using a quadratic programming method to maintain the system stability in the presence of network delay. In additions, a teleoperation experiment is presented to demonstrate the effectiveness of the proposed controller gains adjustment scheme.

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