A Co-design Approach for Bilateral Teleoperation over Hybrid Network

Zeashan Hameed Khan, Denis Genon-Catalot, Jean-Marc Thiriet

18th Mediterranean Conference on Control & Automation
Congress Palace Hotel, Marrakech, Morocco
June 23-25, 2010

A Co-design Approach for Bilateral Teleoperation over Hybrid Network

Zeashan H. Khan, Denis Genon-Catalot and Jean Marc Thiriet

Abstract— **This paper describes a joint approach for control and communication network design for the application of bilateral teleoperation system (BTS). By ensuring a QoS oriented network architecture, a better quality of control (QoC) can be guaranteed despite the presence of time delays and packet losses. In this work, a joint approach is presented for the co-design problem to observe the improvements in QoC by network QoS for the bilateral teleoperation application.**

I. INTRODUCTION

Networked control systems are widely used in manufacturing industry, robotics, biomedical and even in aeronautics and space applications. Teleoperation can be considered as a subclass of NCS if it requires networked communication to close the loop between the operator and a remote slave [1]. Long distance teleoperation employs a communication network to transport command and feedback data between the operator and slave system as direct control is not possible, in scenarios where the teleoperator (slave) is located in hard to reach or dangerous remote areas. In addition, if the remote slave is mobile, a wireless network is the only possible choice. The wireless networks simplify the design and cut-down installation and maintenance cost in industrial systems. However, they can induce significant delays and information loss due to interferences from other electromagnetic sources, path loss and fading phenomenons. In addition, eavesdropping is also a challenging security issue over wireless network.

In teleoperation terminology, bilateral, haptic and force reflecting refers to the same concept as that of force feedback [2]. This augment the quality of teleoperation as compared to the unilateral or camera-only feedback for the actions taken by a distant supervisor. In the literature, generally, bilateral teleoperation utilizes a master-slave pair which communicates over a communication network. Despite interesting features, bilateral teleoperation has limitations and performance dependencies over several factors. The number of tasks they can perform as compared to human are also limited, since the dexterity of teleoperators is poorer than the human dexterity [3]. This even worsens and sometimes destabilize with the added time delays. In addition to stability, bilateral teleoperators are also supposed to provide sufficient transparency [4].

In modeling a communication channel, only time delay is considered during analysis and full knowledge of communication protocol with its flexibilities and limitations are rarely addressed by the control engineers. However, it is interesting to investigate that even if the wave variables are exchanged between master and slave (instead of force and velocity signals), giving a notion of importance to this information or using resource allocation of the network resources can improve the quality of tracking and performance in bilateral teleoperation. This requires a co-design approach [5].

This paper is organized as follows. In Section II, the bilateral teleoperation is described with the position control loop. Section III discusses the QoC while section IV gives the network architecture for bilateral teleoperation. In Section V, an application case study is presented with some results. Section VI concludes the paper.

II. BILATERAL TELEOPERATION WITH POSITION CONTROL

The first architecture proposed by Anderson and Spong in 1989 was based on the passivity for bilateral teleoperation, which assures robustness against the network delays in the loop and speed sensing [6]. This architecture neither guarantees the position tracking in stationary conditions nor force detection during the operation. Thus, an improved scheme utilizing the traditional passivity based approach with an added position control on the master/slave side to track the position and force detection is preferred [7]. The master/slave dynamics as a single degree of freedom (DOF) model can be represented in terms of system's mass and damper characteristics as [8] :

$$
\begin{aligned}
M_m \ddot{x}_m + B_m \dot{x}_m &= F_h - F_m \\
M_s \ddot{x}_s + B_{s1} \dot{x}_s &= F_s - F_e
\end{aligned} \qquad (1)
$$

Where F_m, F_s constitute the control couple applied to motors at the master/slave, M_m, M_s are the inertias, B_m and B_{s1} are the viscous frictions, F_h, F_e are the control couple from the operator and the environment and x_m, x_s are the positions. The force reflection F_s is taken as [7] :

$$
F_s(t) = K_s \int_0^t (\dot{x}_{sd} - \dot{x}_s) ds + B_{s2}(\dot{x}_{sd} - \dot{x}_s) \qquad (2)
$$

We utilize the scattering transformation to assure the passivity of the system in the presence of constant time delays so that the characteristics that describe the channel

This work is supported by the Higher Education Commission (Pakistan) under OSS-06 grant.

Zeashan H. Khan is presently with the Automatic Control department of GIPSA-lab, Université de Grenoble, Grenoble, France. zeashan-hameed.khan@gipsa-lab.inpg.fr

Denis Genon-Catalot is with the Networks and Telecom Department, LCIS, Université de Grenoble, Valance, France. Denis.Genon-Catalot@iut-valence.fr

Jean Marc Thiriet is with the Automatic Control department of GIPSA-lab, Université de Grenoble, Grenoble, France. jean-marc.thiriet@ujf-grenoble.fr

are similar to those of a transmission line without losses. The scattering variables (U_m, U_s, V_m, V_s) are transmitted across the delay line instead of the original velocities and forces. The transformation is as under :

$$U_m = \frac{1}{\sqrt{2b}}(F_m + b\dot{x}_m), \quad V_m = \frac{1}{\sqrt{2b}}(F_m - b\dot{x}_m)$$
$$U_s = \frac{1}{\sqrt{2b}}(F_s + b\dot{x}_{sd}), \quad V_s = \frac{1}{\sqrt{2b}}(F_s - b\dot{x}_{sd}) \qquad (3)$$

Where $\dot{x}_{sd}$ is the derived velocity at the slave and $\dot{x}_m$ is the speed of the master arm. The positive constant *b* plays a critical role in the system response.

It was shown in [7] that the transient error is dependent on delay while in the steady state position tracking $e(t) = x_m(0) - x_s(0)$ is dependent on their initial position difference even when there is no packet loss. If packet losses occur, it will deteriorate the response even more. Thus, the position control loop is added which modifies the system dynamics as :

$$M_m\ddot{x}_m + B_m\dot{x}_m = F_h + F_{back} - F_m$$
$$M_s\ddot{x}_s + B_{s1}\dot{x}_s = F_s + F_{feed} - F_e \qquad (4)$$

In the successive section, we consider the constant delays and the new architecture by adding a position control which permits us to obtain the new control law as follows :

$$F_s = B_{s2}(\dot{x}_{sd} - \dot{x}_s)$$
$$F_{back} = K(x_s(t-T) - x_m)$$
$$F_{feed} = K(x_m(t-T) - x_s)$$
$$F_m(t) = F_s(t-T) + b\dot{x}_m(t) - b\dot{x}_{sd}(t-T)$$
$$\dot{x}_{sd}(t) = \dot{x}_m(t-T) + \frac{1}{b}.F_m(t-T) - \frac{1}{b}.F_s(t) \qquad (5)$$

The stability is proposed with a lyapunov function which puts the condition that :

$$K^2.T^2 < B_m.B_{s1} \qquad (6)$$

which gives a bound on gain *K* with respect to the delay *T* and parameter variations as shown in Fig. 2. In order to respect this criteria, an adaptive gain scheduling could also be used in real time. It has also been remarked in [7] that this control architecture is stable in case of variable packet loss ; however, the performance degrades with increased data losses.

III. QoC in Bilateral Teleoperation

The quality of control generally has the notion of *stability* and *performance*. For the passivity based BTS architecture, the stability refers to the controller guarantees in order to keep the states/output in defined bounds as ensured by the criteria in Eq. 6. The control objective in teleoperation is to ensure the stability and performance despite the variations in the environment and communication QoS.

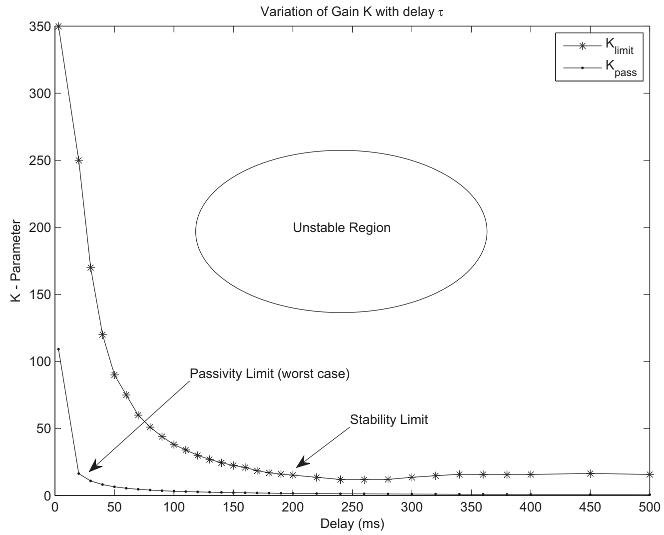

Fig. 2. Passivity Gain variation with delay

A. Stability Requirements

The passivity based control being the mostly used method uses the scattering transformation/wave variable method described above, which requires that the H_∞ norm of the open loop system is limited to unity [9]. This condition is given by the small gain theorem. The QoC is ensured by the force tracking error given as :

$$e_f = F_{back} - F_m + F_e \qquad (7)$$

This error should be bounded for good performance.

1) Force Tracking: The passivity based control requires that the condition of passivity must be satisfied for each subsystem in the teleoperation loop. The communication block acts as a non-passive system which adds energy in the overall system block, otherwise as long as the master and slave respect the passivity criteria, their stability is guaranteed. As known earlier, the delay tolerant architecture proposed by [8] compensates for the time delay by using the active control that ensures passive communication subsystem independent of the constant time delay. However, the response gets sluggish with the increase in delays as the gain decreases significantly [10]. In addition, if the non-linearities in the mechanical systems are included by adding the actuator model, flexible links and joints, backlash etc ; the system passivity is altered. In [11], wave variable notation is used to define the force reflecting teleoperators.

2) Position Tracking: When position control is added to the classical passivity based bilateral teleoperation, the position tracking performance is also important to observe [7]. Integral of absolute error (IAE), time absolute error (ITAE) and root mean square error (RMSE) are some of the position error metrics for QoC [12]. In the present architecture, we are considering the gain K as the QoC parameter as the higher values of K reduces the steady state error effectively thus ensuring better QoC.

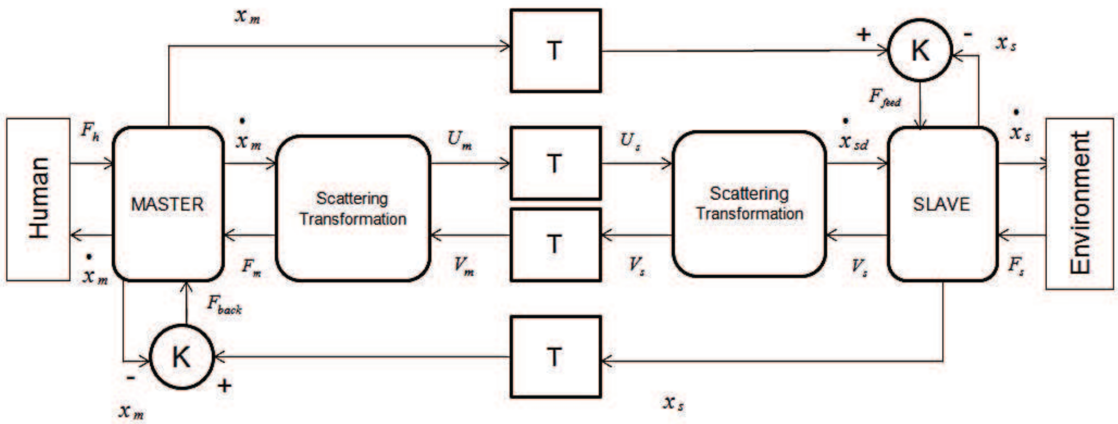

Fig. 1. Bilateral teleoperation with position control loop

B. Performance Requirements

In addition to stability, the performance is also an important factor in bilateral teleoperation. This performance is dependent on the model of human at the master side while that of the environment at the slave end. The damping and stiffness gains therefore change if either of the human or environment changes. As mentioned earlier, the transparence being an important performance parameter, means that the operator should feel like directly interacting. Thus, the transparency is dependent on the human perceived performance, communication effects and the required teleoperator dynamics. It is better quantified in terms of the match between the mechanical impedance of the environment sensed by the slave and the mechanical impedance felt by the operator at the master station [13]. However, there is a tradeoff between transparency and the robust stability design for bilateral teleoperation. In [14], a teleoperator is defined perfectly transparent when the human operator (h) feels the same forces and velocities at the master device as if he was directly manipulating the environment (e). This means that F_h = F_e and V_h = V_e. This essentially results in the hybrid matrix form as :

$$H(s) = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \quad (8)$$

1) Transparence: One of the design objective in BTS is to augment the transparency of the communication channel so that the human operator cannot distinguish between direct interaction with an environment and the teleoperated interaction with a remote environment. In general, the transparency requirements are overly strict and difficult to satisfy in a real systems, especially in time delay systems as the response is retarded. On the other hand, the knowledge of psychophysical effects in human haptic perception is also important as transparency varies with the human experience. This can be used to reduce significant amount of data without much compromising on the human perception.

The transparency objective performance metric requires that the impedance perceived by the human and the environment impedance must be equal [15], i.e. $Z_h = Z_e$ as shown in Fig 3. But in practice, it is not possible due to the non-similarity between master and slave devices, gain adjustments and delays introduced by the network. The stiffness decreases with the increased delay and packet loss rate. The transmitted impedance which is the impedance of the slave seen by the human operator is approximated as an LTI transfer function by $Z_t = \frac{F_m}{V_h}$. Thus, the mechanical impedance Z_t defines the mapping from velocity V_h to force F_m.

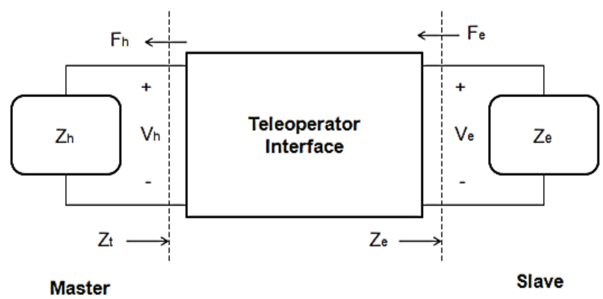

Fig. 3. Two-port model of bilateral teleoperation system

2) Telepresence: It describes the quality of the operator experience that he/she encounters at a distant place as compared to actually being at the remote site. This requires a number of sensors feedback (multi-modal) to augment the telepresence.

IV. Network Architecture for Bilateral Teleoperation

The network architecture is an important consideration in the bilateral teleoperation. In case of hybrid networks where two different MAC and PHY layer technologies are interconnected, end to end QoS configuration is necessary. The QoS is defined as the ability of a network element to have some level of assurance that its traffic and service requirements can be satisfied [16]. The performance metrics of QoS are usually regarded as the availability, delay, jitter,

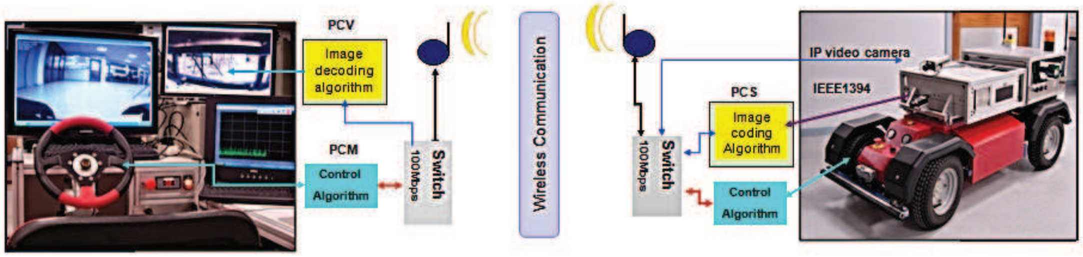

Fig. 4. NeCS-Car Teleoperation Benchmark (NeCS Team GIPSA-lab/INRIA)

throughput and packet loss rate. Thus, QoS manages bandwidth according to the network flexibility and application needs which may be regarded as *managed unfairness*. As bilateral teleoperation requires that the video is sent from slave to master in order to augment the telepresence effects, some QoS policy must be configured even with optimized codecs and video compression. In case of non-QoS communication architecture, adaptation mechanism is necessary for a controlled degradation in video quality.

A wireless communication network between master and slave is the only possibility due to mobility aspects. The control data in teleoperation requires a certain bound on delay and jitter, which can otherwise affect the system performance. The QoS is described in terms of successful reception as well as guaranteed time lines. WLAN 802.11b/g supports only ACK through TCP/IP, otherwise it offers best effort (BE) flows. However, in 802.11e, some QoS options are available based on the priorities for distinct type of flows e.g. voice, video, data etc. In teleoperation, the control data and video flows must be exchanged via either UDP or TCP between the master and slave. The advantage with UDP is that it doesn't require ACK and thus delay is relatively lower without any reception guarantees. TCP, on the other hand requires ACK for every reception, otherwise it retransmits the missing data. However, this causes an unpredictable data arrival time, thus a varying delay.

V. NeCS-Car teleoperation test bench

The NeCS-Car is a dedicated platform for teleoperation funded by the *NeCS Team* at the Control Systems department of GIPSA-lab as shown in Fig. 4. A remote operator can drive the car via a hybrid (Ethernet + WLAN) networked communication by observing the video and experiencing the force feedback. The system has an embedded PC installed on the mobile part while the control station has 2 PCs for video and control system. The embedded network is switched ethernet to communicate between controller, image processor and IP video camera. These devices are connected with a 100 Mbps switch which is further connected to a WLAN router. The on-board control data (speed, position, wheel rotation etc) is sent over UDP, 40 bytes every 1ms (40 Kbps). About 20% of the traffic sent over UDP is lost as there is no acknowledgement for successful data reception. For image data, TCP is used to ensure successful communication of video packets because the operator is totally dependent on the video to drive the car and a little loss of a compressed MPEG stream can emerge into a number of missing frames reducing video quality. The image data is about 40Kb sent every 40ms i.e. 1 Mbps after compression at the mobile platform.

The operating system on all PCs is Windows XP. However, for real time communication of controller, Ardence RTX interface is used. Controller is designed in Matlab/Simulink and it is converted to RTX which is a rapid prototyping product by Quanser. RTX provides a rapid start-up, direct control and ownership of scheduling, higher availability, use of the Windows development tools and common Windows APIs. Real-Time TCP/IP, included with RTX, provides tools to embed high performance real-time networking protocols into systems and applications. This is possible with the A/D and D/A converters on the Data Acquisition and Control Buffer (DACB) communicating with WinCon using the Real Time Execution (RTX) Workshop installed in Simulink. The force feedback is measured by a sensor mounted on the vehicle to capture the torque couple created by opposing forces at the vehicle motor. This force is fed back and realized through a D.C motor.

A. Hybrid Network Architecture

The network architecture uses a hybrid approach in the sense that WLAN 802.11 b/g is used to connect two Ethernet 802.3 networks at the two sides (Master & Slave). The down side of the wireless link is that there is more probability of data corruption and greater packet loss rate. In addition, MAC layer collisions may not be resolved timely which may cause delays or packet drop. In our present architecture, two flows comprising the realtime control data and the IP camera video can be seen. However, QoS support is not available in this architecture. The MOXA WLAN cards only permit to change the RTS threshold which acts as a switch to start the RTS/CTS four way handshake instead of two way basic access mechanism.

The video link is set over TCP to ensure good QoS at the transport layer. This ensures that all packets have successfully reached to the destination and re-transmission is performed for the lost ones. However, excessive re-transmissions can deteriorate the video quality. The operator, however, has the choice to switch the frame rate at a lower value so that the network load can be decreased significantly. We propose an automated way of achieving this objective by evaluating the network QoS online and controlling the video flow accordingly. A fixed packet size of 1514 bytes is used throughout the experimentation.

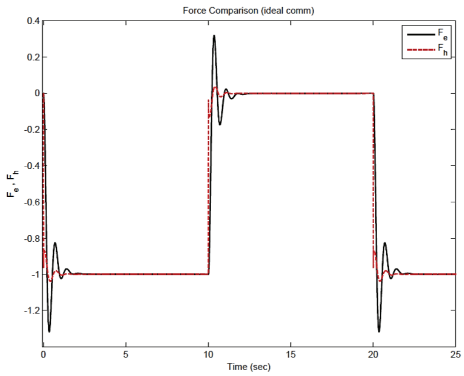

Fig. 5. Environment and Operator force comparison (Network delay = 50ms, Jitter = 10ms)

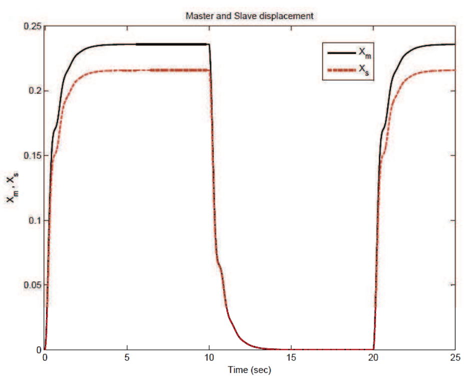

Fig. 6. Environment and Operator position comparison (Network delay = 50ms, Jitter = 10ms)

NeCS-Car parameters used from identification of the master and slave are as follows : M_m = 0.0284 $N.m^2/rd$, M_{s1} = 3.25 $N.m^2/rd$, B_m = 0.0817 N.m.s/rd, B_{s1} = 5.6833 N.m.s/rd. Also, K = 70, B_{s2} = 9 N.m.s/rd and b = 8 in the model. The sampling time T_s is 0.001s. A PI controller is used to improve reversibility with K_p = 10, T_i = 0.2. The backlash in the rack and pinion gear assembly is estimated to be 0.2328 rad ($\approx 13.33°$). To evaluate the transparence of the platform, we have utilized the experimental approach described in [17]. The external impedance and the impedance transmitted to the operator are given as :

$$Z_e(j\omega) = \frac{F_{em}}{s.X_s(j\omega)} \tag{9}$$

$$Z_t(j\omega) = \frac{F_m}{s.X_m(j\omega)} = G_t.Z_e(j\omega) \tag{10}$$

where G_t is the transfer function of the transparence. We have adapted this criteria to our case because the measured force F_{em} depends on the position as described in the model above. We have therefore, the external impedance and the impedance transmitted to the operator as mentioned above.

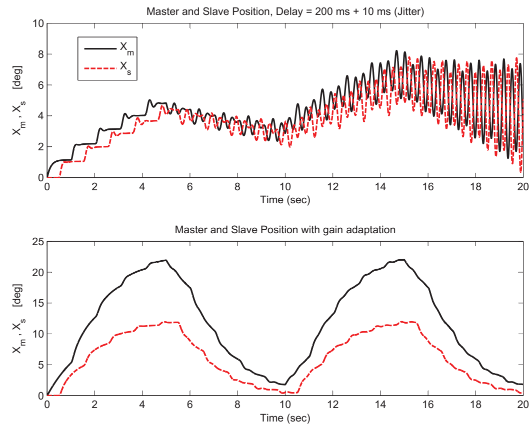

Fig. 7. Gain Adaptation for Position Control

We calculate the inverse of the $\frac{F_{em}}{s.X_s(j\omega)}$ to find G_t which gives us the transfer function of the transparence.

In the network architecture, the switched ethernet based wired part adds a fixed delay around 1 to 2 ms. So this delay can be taken as a small contribution in the total end-to-end delay. Our main focus is on the wireless part which is more susceptible to perturbations and data loss. In Fig. 5 and 6 above, a delay only network model is used to simulate the scattering transformation for control of NeCS-Car. Fig. 7 shows the simulation results that in case of exceeding delays (200 ms + 10 ms jitter) and parameter variations, the stability is altered whereas, a QoS dependent gain adaptation approach keeps the system stable.

B. Fuzzy QoS based Packet rate control

The control architecture, based on [7] and [8], permits to withstand a large delay. However, the passivity condition in Eq. 6 will be violated due to the parameter variations in Master/Slave with changing operator and environment. In addition, packet losses can also deteriorate the transparence which is a key parameter in telepresence. We propose to dynamically parameterize the wireless network to vary the packet rate in order to minimize packet losses and delay. This performance monitor is configured at the master station which alters the video rate by sending a command to slave station.

Fuzzy inference system (FIS) is used in many applications related to QoS evaluation, handoff process, bandwidth control as in [18], [19] and [20]. The sugeno FIS is preferred in online decision due to its simplicity and efficiency.

TABLE I
FUZZY RULE BASE INSIDE THE QOS ESTIMATOR

Rule	DL	PL	QoS	α
1	NE	LW	EX	1
2	NE	HH	GD	1
3	NE	VH	BD	1
4	SL	NE	EX	0.5
5	LG	NE	GD	0.5
6	VL	NE	BD	0.5

We used triangular MFs for delay (DL) and packet losses (PL) as the two inputs of QoS fuzzy inference block. The range of delay varies from 0 to 500 ms, for packet loss it is 0 to 100 % and for QoS it is scaled between 0 and 1. The states used are none (NE), small (SL), large (LG) and very large (VL) for delay ; low (LW), high (HH) and very high (VH) for packet loss and good (GD), bad (BD) and excellent (EX) for QoS. The fuzzy rule base for QoS estimation is shown in Table I, where QoS has more weight for packet loss than delay. This is because information loss has a severe impact on transparence and stability.

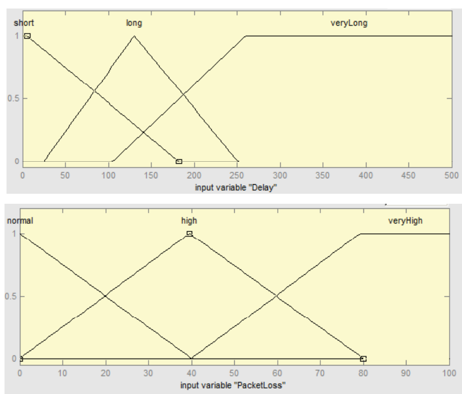

Fig. 8. Membership functions for Fuzzy QoS module

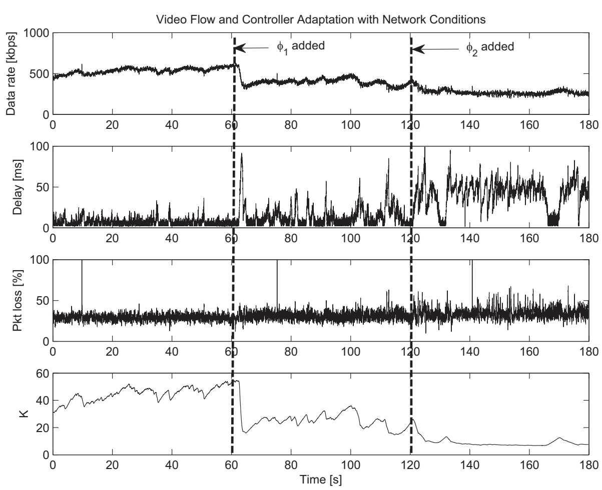

Fig. 9. QoS evaluation for Gain Adaptation

The figure 9 shows a gain adaptation scheme with respect to the QoS estimation as well as the effective packet rate alteration for the video flow at t = 60 sec and 120 sec when Φ_{ext1} = Φ_{ext2} = 3.1 Mbps TCP/IP flows are added to the network. This allows a *graceful degradation* of the control and video quality in the presence of external traffic.

VI. CONCLUSION

The work presented in this paper consists of a fuzzy co-adaptation approach for communication and control with application to bilateral teleoperation. The isolated controller design poses problems in terms of stability and performance objectives of the application when used in NCS. This work is being implemented on the NeCS-Car which is the Networked Control System's benchmark maintained at GIPSA-lab.

VII. ACKNOWLEDGMENTS

The authors gratefully acknowledge the contribution of NeCS-Team (GIPSA-lab/INRIA) for the experimental setup. This work has been supported by the Higher Education Commission of Pakistan under OSS-06 Program.

REFERENCES

[1] F. L. Lian, J. Moyne, and D. Tilbury, "Network design consideration for distributed control systems," *IEEE Transactions on Control Systems Technology*, vol. 10, 2002.

[2] M. Mulder, "Stability in haptic teleoperation - literature review," TU Delft - Mechanical Engineering - Biomechanical Design, Tech. Rep., 2006.

[3] Y. Yokokohji, T. Imaida, and Y. Iida, "Bilateral teleoperation : Towards fine manipulation with large time delay," *Springer-Verlag Berlin*, 2001.

[4] S. Salcudean, "Contorl of teleoperation and haptic interfaces," *Control problems in robotics and automation*, vol. Springer-Verlag LNCIS 230, pp. 51–66, 1998.

[5] A. Mechraoui, Z. H. Khan, J. Thiriet, and S. Gentil, "Co-design for wireless networked control of an intelligent mobile robot," *International Conference on Informatics in Control, Automation and Robotics (ICINCO), Milan, Italy*, 2009.

[6] P. F. Hokayem and M. W. Spong, "Bilateral teleoperation : An historical survey," *Automatica*, vol. Vol. 42, Issue 12, pp. 2035–2057, 2006.

[7] N. Chopra, M. Spong, R. Ortega, and N. E. Barabanov, "On tracking performance in bilateral teleoperation," *IEEE transaction on Robotics*, vol. 22, 2006.

[8] R. J. Anderson and M. W. Spong, "Bilateral control of teleoperation with time delay," *IEEE Transactions on Automatic Control*, vol. 34, pp. 494–501, 1989.

[9] J. J. Slotine and G. E. Niemeyer, "Stable adaptative teleoperation," *IEEE Journal of Oceanic Engineering*, pp. 152–161, 1991.

[10] C. A. Lawn and B. Hannaford, "Performance testing of passive communication and control in teleoperation with time delay," *IEEE Int Conference on Robotics and Automation*, pp. 776–783, 1993.

[11] G. Niemeyer and J. J. E. Slotine, "Stable adaptive teleoperation," *IEEE Journal of Oceanic Engineering*, vol. 16, pp. 152–162, 1991.

[12] G. Franklin, J. Powell, and M. Workman, *Digital Control of Dynamic Systems*, Second ed. Reading, MA : Addison Wesley, 1994.

[13] M. Zhu and S. Salcudean, "Achieving transparency for teleoperator systems under position and rate control," *IEEE International Conference On Robotics and Automation*, pp. 7–12, 1995.

[14] Y. Yokokohji and T. Yoshikawa, "Bilateral control for master-slave manipulators for ideal kinesthetic coupling - formulation and experiment," *IEEE Transactions on Robotics and Automation*, pp. 605–620, 1994.

[15] D. A. Lawrence, "Stability and transparency in bilateral teleoperation," *IEEE Transaction in Robotics and Automation*, vol. 9, pp. 624–637, 1993.

[16] M. Marchese, *QoS Over Heterogeneous Networks*. Wiley, 2007.

[17] K. B. Fite, L. Shao, and M. Goldfarb, "Loop Shaping for Transparency and Stability Robustness in Bilateral Telemanipulation," *IEEE Transaction on Robotics and Automation*, vol. 20, pp. 620–624, 2004.

[18] A. Wilson, A. Lenaghan, and R. Malyan, "Optimising wireless access network selection to maintain qos in heterogeneous wireless environments," *Proceedings of the Wireless Personal Multimedia Communications (WPMC 05), Aalborg, Denmark*, 2005.

[19] R. Zhang and Y. Phillis, "Admission control and scheduling in simple series parallel networks using fuzzy logic," *IEEE Transactions on Fuzzy Systems*, vol. 9, p. 307314, 2001.

[20] Z. Li, W. Wang, and Y. Jiang, "Managing quality-of-control and requirement-of-bandwidth in networked control systems via fuzzy bandwidth scheduling," *International Journal of Control, Automation, and Systems*, vol. 7(2), pp. 289–296, 2009.