TOWARDS DEADBAND CONTROL IN NETWORKED TELEOPERATION SYSTEMS

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Abstract: One of the key challenges in current bilateral teleoperation systems is the high data packet rate necessary for the transmission of the sampled command and sensor data. We present a novel, psychophysically motivated approach to reduce the packet rate based on a deadband transmission strategy. Data packets are only sent if the sampled signal changes more than a given threshold value. The threshold value is adjusted to match the just noticeable difference in human haptic perception. Missing data at the receiver are reconstructed by a modified "hold last sample" algorithm that guarantees passivity/stability. Our experiments validate that the proposed approach leads to a considerable reduction (up to 85%) of the packet rate without sacrificing the human haptic perception of the remote environment.

Keywords: teleoperation, communication networks, deadband, human perception

1. INTRODUCTION

In a multimodal teleoperation system a human operator commands a remote robot (teleoperator) by manipulating the human system interface (HSI). The multimodal sensor data acquired at the teleoperator are fed back and displayed to the operator. Application areas of such systems reach from tele-surgery, -maintenance to tele-training and -entertainment, see (Buss and Schmidt, 1999). Considering video and audio feedback as state-of-the-art multimedia we focus on the haptic (force) feedback system.

In a teleoperation system a global control loop is closed over the human operator and the generally unknown remote environment. In order to guarantee stability of teleoperation systems the passivity concept has sucessfully been applied (Anderson and Spong, 1989). As a result velocity and force signals are exchanged between the HSI and the teleoperator.

The sampled velocity and force data are transmitted over a packet switched communication network as, e.g., the Internet. The local control loops at the HSI and the teleoperator operate at a sampling rate in the range of 500 – 1000 Hz. In order to keep the packetization delay as small as possible every set of sampled data is sent in individual packets. High packet rates (500 to 1000 packets per second) are hard to maintain over long distance packet switched networks. Additionally the probability of congestion is increased leading to higher transmission delay and packet loss.

In (Otanez *et al.*, 2002; Ishii and Basar, 2004) network traffic reduction in networked control systems is achieved by applying deadband control.

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The data packets are sent over the communication network only if the signal value changes more than a given threshold.

In this paper we present a novel psychophysically motivated approach for packet rate reduction in teleoperation applications over the Internet. It is based on the deadband control approach. According to results from psychophysics there exist perception thresholds (just noticable difference, JND) in human haptic perception for velocity and force signals (Burdea, 1996; Jones and Hunter, 1992). Hence we propose an adaptive deadband, i.e., the size of the deadband increases proportionally with the magnitude of the transmitted velocity/force signal. Deadband control results in empty sampling instances at the receiver side. In (Otanez *et al.*, 2002) the values of the missing data are estimated by holding the value of the last received sample. The "hold last sample" (HLS) algorithm is non-passive as shown in (Hirche and Buss, 2004); as a result the stability of the teleoperation system cannot be guaranteed. Here we propose a modified HLS algorithm that guarantees passivity/stability of the overall system. In order to investigate the potential of this approach in this preliminary study we assume that the communication channel has no delay and no packet loss. The performance of the teleoperation system is commonly evaluated by objective measures such as the position and force tracking in (Yokokohji and Yoshikawa, 1994). According to numerous psychophysical studies of human haptic perception, see ,e.g., (Burdea, 1996), these objective measures turn out to be too strict in general. Consequently we determine the optimal deadband threshold values by means of psychophysical experiments.

The remainder of this paper is organized as follows. In Section 2 we present our deadband transmission approach followed by a stability consideration in Section 3. We describe the psychophysical experiment that is used to evaluate the appropriate transmission parameters along with its results in Section 4. Section 5 concludes this paper with a brief discussion and an outline of future work.

2. TELEOPERATION SYSTEMS

2.1 Architecture

A teleoperation system basically consists of a force feedback capable HSI (variables indexed $_h$) and the teleoperator (index $_t$) interacting with an usually unknown remote environment (index $_e$), see Fig. 1. In bilateral teleoperation the human manipulates the HSI applying the force f_h. Based on stability arguments in the standard architecture the HSI velocity $\dot{x}_h$ is communicated to the

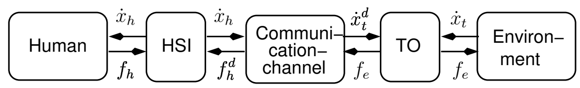

Fig. 1. Teleoperation system architecture

teleoperator where the local velocity control loop ensures the tracking of the desired teleoperator velocity $\dot{x}_t^d$ (^{d} denotes desired). The force f_e sensed at the remote site, resulting from the interaction with the environment, is transmitted back to the HSI serving as the reference signal f_h^d for the local force control.

2.2 Stability of Teleoperation Systems

The HSI and the teleoperator are connected through a communication network closing a global control loop via the human operator. The most eligible approach to analyze such complex systems with partly unknown dynamics is the passivity approach. Passivity is a sufficient condition for stability of the teleoperation system. A complex system of interconnected network elements (n-ports) is passive if each of the subsystems is passive. A passive element is one for which, given zero energy storage at $t = 0$, the property

$$\int_0^t P_{in}\,\mathrm{d}\tau = \int_0^t \boldsymbol{u}^T \boldsymbol{y}\,\mathrm{d}\tau \geq 0 \quad \forall t > 0 \qquad (1)$$

holds, with P_{in} denoting the power stored or dissipated in the system, $\boldsymbol{u}$, $\boldsymbol{y}$ being the input and output vector. In classical teleoperation system architectures, as proposed in (Anderson and Spong, 1989) the HSI and teleoperator exchange velocity $\dot{x}$ and force f signals as shown in Fig. 1. The mapping from velocity to force is generally passive, hence the teleoperator/environment and the HSI/human are assumed to be passive subsystems. If the communication subsystem including the deadband controller at the sender and the data reconstruction at the receiver is passive as well, then the overall system is passive and thereby stable.

2.3 Performance of Teleoperation Systems

The design goal of teleoperation systems is that the human operator cannot distinguish between direct interaction with an environment and teleoperated interaction with an remote environment. Then the teleoperation system is called *transparent*. In order to evaluate the transparency commonly objective performance metrics are employed. For transparency the position and force at the HSI and the teleoperator are required to be equal in (Yokokohji and Yoshikawa, 1994); in (Lawrence, 1993) the equality of the dynamics displayed to the operator and of the environment is considered. These requirements do not incorporate the knowledge of psychophysical effects in human haptic perception. Aiming at transparent teleoperation they are overstrict in general. According to numerous psychophysical studies the human being is only able to discriminate velocity/force changes which have a magnitude proportional to the velocity/force itself. The detection threshold, called *just noticable difference* (JND), for force perception with hand and arm is around 10% (Burdea, 1996), for velocity around 8% (Jones and Hunter, 1992). These results encourage the introduction of adaptive deadbands proportional to the magnitude of the value to be transmitted over the communication network.

3. DEADBAND CONTROL

3.1 Definition

We propose an adaptive deadband control for the transmission of the sampled velocity and force signals in a teleoperation system. The deadband controller compares the previous value $x(t')$ sent over the network to the most recent value $x(t)$. If the absolute value of the difference between $x(t')$ and $x(t)$ is within the deadband then no update is sent over the network. If the difference is outside the value $x(t)$ is transmitted and a new deadband is established around the value $x(t)$. Based on the findings from psychophysics we propose an adaptive deadband that grows linearly by factor ϵ with the magnitude of the value $x(t')$. The absolute value Δ of the deadband is then given by

$$\Delta_{x(t')} = \epsilon \cdot |x(t')|. \quad (2)$$

If the signal $x(t')$ is close to the origin the deadband becomes infinitely small. As there exists a lower and upper absolute threshold in human haptic perception for velocity/force signals we propose to limit the deadband $\Delta_{min} \leq \Delta \leq \Delta_{max}$. If now the most recent transmitted value is close to the origin $|x(t')| < \Delta_{min}$ it may happen that the input to the deadband controller $x(t)$ changes the sign. The signs of the signals though define the direction of the power flow in the communication subsystem as we will see in the next section. The invariance of the power flow direction is necessary for our stability considerations. Consequently as soon as the input $x(t)$ changes the sign it must be transmitted. Therefore it is necessary to weaken the lower bound Δ_{min}. Close to the origin the deadband is unequally spaced such that

$$|x(t)| \in [0, |x(t')| + \Delta_{min}] \quad \text{if } |x(t')| < \Delta_{min} \quad (3)$$

holds and far from the origin

$$|x(t)| \in [|x(t')| \pm \Delta_{x(t')}] \quad \text{if } |x(t')| \geq \Delta_{min}. \quad (4)$$

With this definition of the deadband the sign consistency between transmitted values and current values at the sender is guaranteed

$$x(t)x(t') \geq 0. \quad (5)$$

In the following we assume that the deadband denoted by Δ fulfills the sign convention. We define the deadband control operator by

$$\Omega(t) = \begin{cases} 1 \text{ if } x(t) \in [x(t') \pm \Delta_{x(t')}] \\ 0 \text{ otherwise.} \end{cases} \quad (6)$$

If $\Omega(t) = 1$ the deadband is active and no data is sent.

Active deadband control results in empty sampling instances at the receiver side where the transmitted velocity/force signals act as set values to the corresponding control loop. The missing data $x'(t)$ need to be reconstructed by some reconstruction algorithm $\zeta(x(t'), t)$. Under the assumption that the communication channel has no delay and no packet loss the recontruction operator can be denoted by

$$x'(t) = \begin{cases} \zeta(x(t'), t) \text{ if } \Omega(t) = 1 \\ x(t) \text{ otherwise.} \end{cases} \quad (7)$$

With the same argumentation as for the deadband controller we require that the direction (sign) of the reconstructed value is equal to the transmitted value $x(t')\zeta(x(t'), t) \geq 0$. This means that if a positive force applies to the teleoperator, the HSI displays a positive force. In the following the stability for different data reconstruction algorithms $\zeta(x(t'), t)$ is investigated.

3.2 Stability

In order to guarantee the passivity/stability of the overall system the bilateral communication subsystem including the deadband algorithm at each sender, the channel, and the data reconstruction strategy at the corresponding receiver side must be passive, see Fig. 2.

The passivity of the communication subsystem can be examined by computing the energy balance

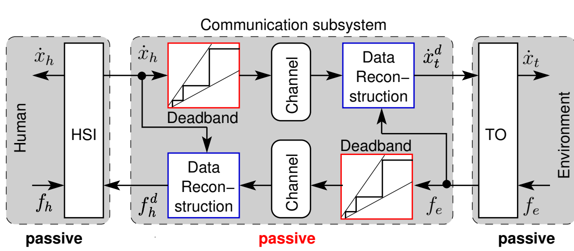

Fig. 2. Deadband controlled teleoperation system

of the bilateral communication line which for passivity according to (1) must fulfill

$$\int_0^t (\dot{x}_h f_h^d - \dot{x}_t^d f_e)\,\mathrm{d}\tau \geq 0 \quad \forall t > 0 \qquad (8)$$

for all admissible inputs $\dot{x}_h$ and f_e. Without the deadband control equality holds as $\dot{x}_t^d = \dot{x}_h$ and $f_h^d = f_e$ for all times t; the communication subsystem is passive (lossless).

In networked control systems the missing data values during active deadband control, $\Omega(t) = 1$, are commonly reconstructed by a simple "hold last sample" $\zeta(x(t'), t) = x(t')$. Applied to the teleoperation system this means

$$\begin{aligned} f_h^d(t) &= f_e(t') \\ \dot{x}_t^d(t) &= \dot{x}_h(t'), \end{aligned} \qquad (9)$$

where $\dot{x}_h(t')$ and $f_e(t')$ represent the value of the last packet sent. With this algorithm the communication subsystem is not passive. For a sketch of a proof let us assume that the input values to the deadband controller according to (4) take values

$$\begin{aligned} \dot{x}_h(t) &= \dot{x}_h(t') - \mathrm{sign} f_e(t) \cdot \delta \\ f_e(t) &= f_e(t') + \mathrm{sign} \dot{x}_h(t) \cdot \delta \end{aligned}$$

with $\delta \in (0, \Delta]$. Then with (9) it is easy to show that the first term of the sum in (8) $\dot{x}_h(t) f_h^d(t) < \dot{x}_h(t') f_e(t')$ and the latter term of the sum $\dot{x}_t^d(t) f_e(t) > \dot{x}_h(t') f_e(t')$. Hence the first term of the sum in (8) is smaller than the latter one. The passivity condition is therefore violated and the "hold last sample" strategy is not passive. Passivity hence stability of the teleoperation system cannot be guaranteed.

In order to guarantee passivity of the communication subsystem we propose a modified "hold last sample" algorithm during active deadband control $\Omega(t) = 1$. *Theorem:* The data reconstruction algorithm

$$\begin{aligned} f_h^d(t) &= f_e(t') + \mathrm{sign}\{\dot{x}_h(t)\} \cdot \Delta_{f_e(t')} \\ \dot{x}_t^d(t) &= \dot{x}_h(t') - \mathrm{sign}\{f_e(t)\} \cdot \Delta_{\dot{x}_h(t')}, \end{aligned} \qquad (10)$$

with the Δ designed according to the sign consistency condition on the deadband controller (5) and the reconstruction algorithm (7) from Sec. 3.1 such that $f_h^d(t) f_e(t') \geq 0$ and $\dot{x}_t^d(t) \dot{x}_h(t') \geq 0$ holds, passifies the communication subsystem.
Proof: As the subsystems human/HSI and teleoperator/environment are assumed to be passive, hence $\dot{x}_h f_h^d \geq 0$ and $\dot{x}_t^d f_e \geq 0$ holds $\forall t > 0$, it is sufficient to show that $|\dot{x}_h||f_h^d| \geq |\dot{x}_t^d||f_e|$ is satisfied $\forall t > 0$. Looking at the first term in this inequality with (4) we have $|\dot{x}_h(t)| \geq |\dot{x}_h(t')| - \Delta_{\dot{x}_h(t')}$. From the passivity condition on the subsystem human/HSI follows that the signs of $f_h^d(t)$ and $x_h(t)$ are equal, further by assumption the signs of $f_h^d(t)$ and $f_e(t')$ are equal as well. Hence, with the first line of (10) the reconstructed value can be rewritten as $|f_h^d(t)| = |f_e(t') + \Delta_{f_e(t')}|$. In consequence

$$|\dot{x}_h||f_h^d| \geq (|\dot{x}_h(t')| - \Delta_{\dot{x}_h(t')}) \cdot |f_e(t') + \Delta_{f_e(t')}|$$

holds $\forall t > 0$. With a similar argumentation we can show that

$$|\dot{x}_t^d||f_e| \leq (|\dot{x}_h(t')| - \Delta_{\dot{x}_h(t')}) \cdot |f_e(t') + \Delta_{f_e(t')}|$$

is true $\forall t > 0$. Hence $|\dot{x}_h||f_h^d| \geq |\dot{x}_t^d||f_e|$ is true. The first term in (8) is always equal or larger than the latter one fulfilling the passivity condition. The modified HLS is therefore passive.

The communication subsystem is passive rendering the overall system passive and thereby stable.

3.3 Position Update

The deadband control for the velocity signal induces a velocity error between the HSI and the teleoperator. As a result the teleoperator position drifts away from the HSI position. The position drift does not only deteriorate the transparency, but may also drive the system to inoperability if the HSI or the teleoperator reaches the limit of its workspace. In (Chopra *et al.*, 2003) the velocity/force architecture is extended by a position feedforward. It is designed with a saturated position controller at the teleoperator such that the passivity condition is not violated. With the same arguments we propose to send a HSI position update together with the velocity data packets in order to improve the position tracking.

3.4 Simulations

The behavior of the proposed strategy is now investigated in simulations. The HSI as well as the teleoperator are modeled as identical mass-damper systems (mass $m = 0.23$kg, damping $b = 0.04$kg/s). The human acts like a spring-damper system (damping $b_{hu} = 1$kg/s, spring $k_{hu} = 1000$N/m) additionally applying an sinusoidal force with a frequency of 2 rad/s and an amplitude of 100N. The environment is given by a spring-damper system (damping $b_e = 1$kg/s, spring $k_e = 10$N/m). All simulations are performed with an adaptive deadband of $\epsilon = 0.20$.

The effect of the deadband control and the data reconstruction algorithms is shown in Fig. 3. Note the increasing size of the deadband with increasing velocity magnitude. Depending on the sign of the force the modified HLS reconstructs the signal either at the lower or upper limit according to (10).

In Fig. 4 the computed energy balance of the communication subsystem (8) is shown for the

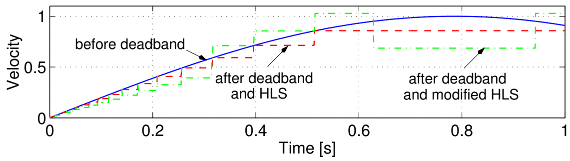

Fig. 3. Effect of deadband and data reconstruction

HLS and our modified HLS algorithm. Clearly, the HLS is non-passive as the energy balance is negative, hence the HLS generates energy. The modified HLS is strictly passive validating our approach.

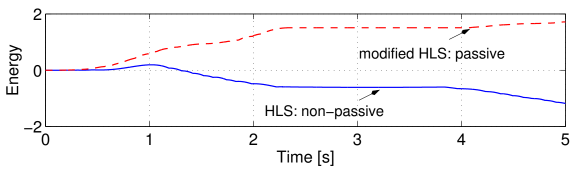

Fig. 4. Energy balance of the communication

The position updating from the HSI increases the performance in terms of position tracking as shown in Fig. 5, where the normed position error $|x_h - x_t|/|x_{h,max}|$ is depicted. Without position update the teleoperator drifts away from the HSI.

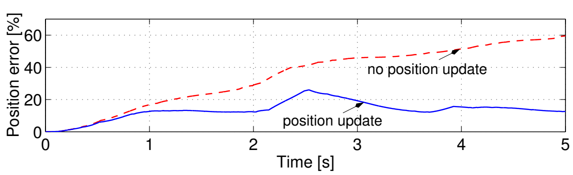

Fig. 5. Normed position error

4. PSYCHOPHYSICAL EXPERIMENTS

4.1 Experimental Setup

Psychophysical experiments were conducted in order to find an appropriate value for ϵ in (2). In this study we apply a general deadband threshold for the force and the velocity signals. The minimal deadband Δ_{min} is set heuristically to a small value for the force of 0.02N and for the velocity of 0.001rad/s. As the displayable velocities and forces are far below the upper human perception threshold, the maximal deadband Δ_{max} is not set.

The experimental setup consists of two identical 1-DOF haptic displays connected to a PC and a stiff wall as the environment, see Fig. 6. The angle is measured by an incremental encoder, the force by a strain gauge. The sensor data are processed in the PC where all control algorithms (HSI force control, teleoperator velocity control) including the deadband control are implemented.

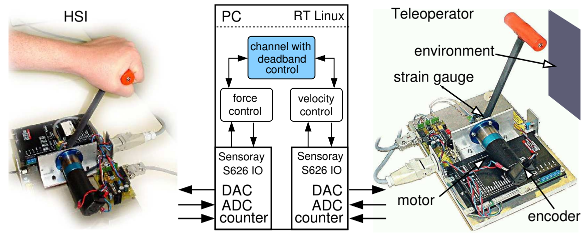

Fig. 6. Experimental setup

4.2 Procedure

Altogether 14 subjects (aged 20–50) were tested for their detection threshold of the deadband parameter ϵ. There were three female and eleven male subjects. Only 3 of the subjects had an idea what the distortion the deadband parameter introduces in the system would feel like. Those 3 had also prior contact with the experimental setup. The other eleven subjects did not know what to expect.

The subjects were told to operate with their preferred hand. They were equipped with earphones to mask the sound the device motors generate. The view to the teleoperator device was blocked so no information could be drawn from the teleoperator behavior. During a familiarization phase subjects were told to feel operation in free space and in contact with a stiff wall without deadband control applied. As soon as they felt familiar with the system the measurement phase began.

In the experiment detection thresholds for the deadband parameter ϵ were determined using a three interval forced choice (3IFC) paradigm. The subjects were presented with three consecutive 20s intervals in which they should operate the system. In two of the intervals the system worked without the deadband algorithm just as in the familiarization phase. In one of the three intervals which was randomly determined the deadband algorithm with a certain value ϵ was applied. Every three intervals the subject had to tell which of the intervals felt different than the other two. The experiment started with a deadband parameter $\epsilon = 2.5\%$ and was increased after every incorrect answer up to maximal 25%. When an answer was correct, the same value was used again until 3 consecutive right answers were given. After this first pass, the subjects were told how the distortion feels like and with what kind of technique they should be able to perceive it best. Then the value ϵ was decreased to 2.5% again and successively increased again using the same procedure as before. After another 3 consecutive right answers ϵ was reduced by 50% without telling the subjects and the procedure was repeated. The mean value of the three ϵ values at which the consecutive right answers occurred were taken as the deadband detection threshold for the specific subject.

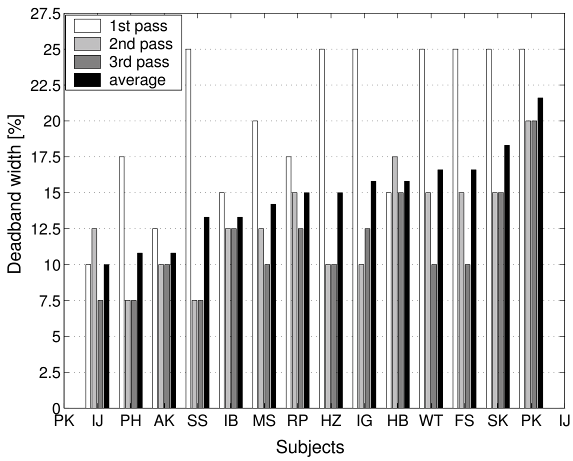

Fig. 7. Overview of the subjects' results

The specific results for every subject presented in Fig. 7 show that no one managed to feel the distortion introduced by the 2.5% and 5% deadband and only very few could discriminate 7.5%, and that only after learning how the distortion feels like. The results correspond to the JND values for force perception with hand and arm that has been determined to be around 10% , for velocity around 8%.

The potential of the adaptive deadband control approach to reduce network traffic can be seen in Fig. 8, where the average packet rates measured during the psychophysical experiments are depicted as a function of the deadband width. The packet rates for velocity packets are already at 25% of the non-deadband rate at a deadband size of $\epsilon = 10\%$ and keep falling with increasing deadband size. Packet rate characteristics for force packets show an even better behavior. Already at $\epsilon = 2.5\%$ we observe a packet rate of under 10% of the original rate. With increasing deadband the force packet rates fall below 5% of the rate without deadband. As result we achieve an overall reduction of the packet rate in the teleoperation system of 85%, i.e. only 15% of the packets containing haptic information need to be transmitted without impairing transparency (at $\epsilon = 10\%$).

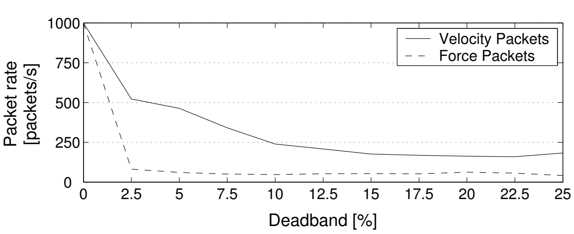

Fig. 8. Influence of the deadband width on packet rates

5. CONCLUSIONS

The proposed psychophysically motivated adaptive deadband control can significantly reduce (up to 85%) network traffic in a teleoperation system without impairing transparency. The data reconstruction by a modified “hold last sample” passifies the communication subsystem guaranteeing the passivity/stability of the overall system. Psychophysical experiments are performed to validate the proposed approach.

The presented algorithm is to our knowledge the first approach exploiting human haptic perception to reduce the data rate of haptic information.

REFERENCES

Anderson, R. and M. Spong (1989). Bilateral control of teleoperators with time delay. In: *IEEE Transactions on Automatic Control*. Vol. 34. pp. 494–501.

Burdea, Grigore C. (1996). *Force and Touch Feedback for Virtual Reality*. Wiley.

Buss, M. and G. Schmidt (1999). Control problems in multi-modal telepresence systems. In: *Advances in Control: Highlights of the 5th European Control Conference ECC'99 in Karlsruhe, Germany* (P. M. Frank, Ed.). pp. 65–101. Springer.

Chopra, N., M. W. Spong, S. Hirche and M. Buss (2003). Bilateral teleoperation over internet: the time varying delay problem. In: *Proceedings of the American Control Conference*. Denver, Colorado. pp. 168–173.

Hirche, S. and M. Buss (2004). Packet loss effects in passive telepresence systems. In: *Proceedings of the IEEE Conference on Decision and Control*. Atlantis, Bahamas. to appear.

Ishii, H. and T. Basar (2004). An analysis on quantization effects in H^∞ parameter identification. In: *Proceedings of the International Conference on Control Applications*. Taipei,Taiwan. pp. 468–473.

Jones, L. A. and I. W. Hunter (1992). Human operator perception of mechanical variables and their effects on tracking performance. *Advances in Robotics* **42**, 49–53.

Lawrence, D.A. (1993). Stability and Transparency in Bilateral Teleoperation. *IEEE Transactions on Robotics and Automation* **9**(5), 624–637.

Otanez, P. G., J. R. Moyne and D. M. Tilbury (2002). Using deadbands to reduce communication in networked control systems. In: *Proceedings of the American Control Conference*. Anchorage, Alaska.

Yokokohji, Y. and T. Yoshikawa (1994). Bilateral Control of Master-Slave Manipulators for Ideal Kinesthetic Coupling Formulation and Experiment. *IEEE Transactions on Robotics and Automation* **10**(5), 605–619.