TOWARDS DEADBAND CONTROL IN NETWORKED TELEOPERATION SYSTEMS

S. Hirche[1], P. Hinterseer[2], E. Steinbach[2], and M. Buss[1]

[1] *Institute of Automatic Control Engineering*
[2] *Institute of Communication Networks*
Technische Universität München
D-80290 München, Germany

{S.Hirche, M.Buss}@ieee.org
{ph, Eckehard.Steinbach}@tum.de

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. In this paper a novel, psychophysically motivated approach to reduce the packet rate based on a deadband approach is proposed. Data packets are only sent if the sampled signal changes more than a given threshold, which is adjusted to match the "just noticeable difference" in human haptic perception. On the receiver side, untransmitted data is reconstructed by a passified "hold last sample" algorithm that guarantees the stability of the teleoperation system. Psychophysical 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. Considering video and audio feedback as state-of-the-art multimedia the focus is on the haptic (force) feedback system.

In teleoperation systems a global control loop is closed by the human operator and the usually unknown remote environment. The passivity concept is suitable to guarantee stability of teleoperation systems (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 sampling rates in the range of 500 – 1000 Hz. In order to keep the packetization delay as small as possible, commonly 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.

[1] www.lsr.ei.tum.de
[2] www.lkn.ei.tum.de

In (Otanez *et al.*, 2002; Ishii and Basar, 2004) network traffic reduction in networked control systems is achieved by applying deadband control. The data packets are sent over the communication network only, if the signal value changes more than a given threshold.

In this paper a novel, psychophysically motivated approach for packet rate reduction in teleoperation applications over the Internet is presented. 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), that proportionally increase with the signal magnitude. Accordingly, the deadband control approach considered here, is based on a relative deadband definition. As not all sampled data are transmitted, deadband control results in empty sampling instances at the receiver side. In (Otanez *et al.*, 2002) the values of the missing data are reconstructed by holding the value of the last received sample. It is shown that the "hold last sample" (HLS) algorithm on velocity and force signals is not passive; as a result the stability of the teleoperation system within the passivity framework cannot be guaranteed. A passified HLS algorithm is proposed, that guarantees passivity/stability of the overall system. In order to show the potential of this approach in this study the communication channel is assumed without delay and packet loss, an extension of the approach for the constant delay case is presented in a companion papern (Hirche *et al.*, 2005). 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, the appropriate deadband threshold values is determined in psychophysical experiments.

The remainder of this paper is organized as follows. In Section 2 our deadband transmission approach is introduced, followed by stability considerations in Section 3. The psychophysical experiment along with its result is presented in Section 4. Section 5 concludes this paper with a brief discussion.

2. TELEOPERATION SYSTEMS

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

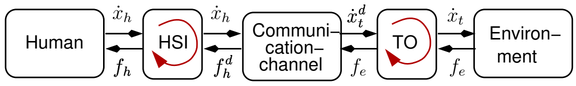

Fig. 1. Teleoperation system architecture

on stability arguments in the standard architecture the HSI velocity $\dot{x}_h$ is communicated to the 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 measured at the remote site, which results 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.

2.1 *Stability by Passivity Approach*

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 its elements is passive. A passive element is one for which, given zero initial energy storage $E_{in}(0) = 0$, the condition

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

holds for all admissible inputs $\boldsymbol{u}$ and outputs $\boldsymbol{y}$. 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. For passivity of the communication subsystem its energy balance (1) with $\boldsymbol{u} = []^T$ and $\boldsymbol{y} = []^T$ must satisfy

$$E_{c,in}(t) = \int_0^t (\dot{x}_h f_h^d - \dot{x}_t^d f_e) \, \mathrm{d}\tau \geq 0 \quad \forall t > 0. \quad (2)$$

If the communication subsystem is passive then the teleoperation system is passive and thereby stable.

2.2 *Transparency*

The design goal of teleoperation systems is that the human operator cannot distinguish between direct interaction with the environment and teleoperated interaction with the 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. In the context of 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 relative deadbands proportional to the magnitude of the value to be transmitted over the communication network.

3. DEADBAND CONTROL

Based on these findings from psychophysics a relative deadband control for the transmission of the sampled velocity and force signals in a teleoperation system is proposed. For the following explainations the symbol x represents the signal to be transmitted, furthermore for the ease of notation the following considerations are done in continuous time, the results equivalently hold for the discrete time case.

3.1 Definition

The deadband controller compares the previous value $x(t')$ sent over the network to the most recent value $x(t)$ with $t > t'$. If the absolute value of the difference $|x(t) - x(t')|$ is smaller than the deadband width Δ then no update is sent over the network. Otherwise the value $x(t)$ is transmitted and a new deadband is established. The relative deadband grows linearly by factor ϵ with the magnitude of the value $x(t')$. The absolute value Δ of the deadband is then given by

$$\Delta_{x(t')} = \epsilon \cdot |x(t')|. \tag{3}$$

The instances of packet transmission can now be described by the event indicato

$$\Omega(t) = \begin{cases} 1 \text{ if } |x(t) - x(t')| \geq \Delta_{x(t')} \\ 0 \text{ otherwise,} \end{cases} \tag{4}$$

indicating a 'packet sent' at time t if $\Omega(t) = 1$.

As there exist lower and upper absolute threshold in human haptic perception for velocity/force signals the absolute deadband value is bounded $\Delta_{min} \leq \Delta \leq \Delta_{max}$. If now the most recently transmitted value is close to the origin $|x(t')| < \Delta_{min}$ it may happen that the input signal to the deadband controller $x(t)$ changes the sign. For transparency the equality of the direction of motion or force at the HSI and the teleoperator is required, otherwise the teleoperator could move into the opposite direction of the HSI for example. Consequently, as soon as the input $x(t)$ changes the sign it must be transmitted. Therefore close to the origin the deadband is unequally spaced, while far from the origin the standard definition (3) applies. In order to consider this exception the deadband is implicitely defined with

$$|x(t)| \in \begin{cases} [0, |x(t')| + \Delta_{min}) & \text{if } |x(t')| < \Delta_{min} \\ [|x(t')| \pm \Delta_{x(t')}] & \text{if } |x(t')| \geq \Delta_{min}, \end{cases} \tag{5}$$

where the first case correspond to the exception made close to the origin. With this definition, the sign consistency

$$x(t)x(t') \geq 0, \tag{6}$$

between transmitted values and current values on the sender side is guaranteed.

As not all data samples are transmitted, 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 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 output $x'(t)$ of the communication subsystem can be denoted by

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

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 $x(t')\zeta(x(t'), t) \geq 0$, i.e. a positive force applied to the teleoperator results in a positive force displayed at the HSI. In the following the stability for different data reconstruction algorithms $\zeta(x(t'), t)$ is investigated.

3.2 Stability

In order to guarantee the stability of the teleoperation system the bilateral communication subsystem must be passive, i.e. the energy balance according to (2) must be non-negative. The communication subsystem includes the deadband algorithm, the communication channel, and the data reconstruction strategy in the forward and the backward path as illustrated in Fig. 2. During the time intervals of packet transmission, corresponding to the upper case in (7), the communication subsystem is passive (lossless). For passivity of the communication subsystem it is sufficient to show, that the energy balance for the time intervals of data reconstruction (lower case) is non-negative.

3.2.1. Energy Generation by HLS A common reconstruction algorithm in networked control systems is the "hold last sample" $\zeta(x(t'),t) = x(t')$. Applied to the teleoperation system this means

$$\begin{aligned} f_h^d(t) &= f_e(t') \\ \dot{x}_t^d(t) &= \dot{x}_h(t'), \end{aligned} \tag{8}$$

where $\dot{x}_h(t')$ and $f_e(t')$ represent the value of the most recent packet sent. With this algorithm the communication subsystem is not passive. For a sketch of a proof the energy balance (2) is computed for a time interval between two consecutively sent packets, assuming zero energy storage a the beginning of the interval. If the signals on the sender sides 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 (8) it is easy to show that the inequalities $\dot{x}_h(t) f_h^d(t) < \dot{x}_h(t') f_e(t')$ and $\dot{x}_t^d(t) f_e(t) > \dot{x}_h(t') f_e(t')$ are true. The energy balance (2) is negative for the considered time interval, the passivity condition (2) is violated. The HLS applied to velocity/force signals is not passive.

3.2.2. Passified HLS In order to guarantee passivity of the communication subsystem a passified HLS is proposed for data reconstruction. Therefore the HLS (8) is extended reconstructing the signal with a worst case estimation.

Theorem: The data reconstruction algorithm

$$\begin{aligned} f_h^d(t) &= f_e(t') + \mathrm{sign}\{\dot{x}_h(t)\} \cdot \Delta_{f_e(t')} \\ \dot{x}_t^d(t) &= \dot{x}_h(t') - \mathrm{sign}\{f_e(t)\} \cdot \Delta_{\dot{x}_h(t')}, \end{aligned} \tag{9}$$

with the Δ designed according to the sign consistency condition on the deadband controller (6) and the reconstruction algorithm (7) 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.
Sketch of proof: As the subsystems human/HSI and teleoperator/environment are assumed to be passive with $\dot{x}_h f_h^d \geq 0$ and $\dot{x}_t^d f_e \geq 0$, it is sufficient to show that $|\dot{x}_h||f_h^d| \geq |\dot{x}_t^d||f_e|$ is satisfied $\forall t > 0$. With (5) clearly $|\dot{x}_h(t)| \geq |\dot{x}_h(t')| - \Delta_{\dot{x}_h(t')}$ holds. With the passivity condition on the human/HSI subsystem and the sign consistency condition (6) follows that the signs of $f_h^d(t)$, $x_h(t)$ and $f_e(t')$ are equal. Hence, with the first line of (9) 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 it can be shown 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 (2) is always equal or larger than the latter one, rendering the energy balance non-negative. Energy is not generated with the passified HLS.

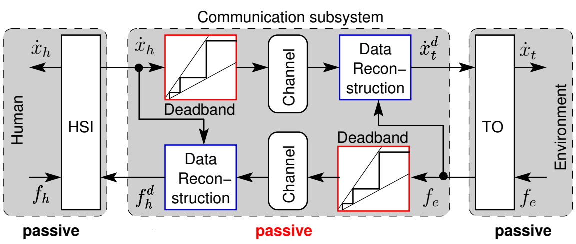

Fig. 2. Deadband controlled teleoperation system

The passified HLS as data reconstruction results in a passive communication subsystem rendering the overall system passive and thereby stable.

3.3 Position Update

The data reconstruction of the velocity signal induces a velocity error between the HSI and the teleoperator. As a result the teleoperator position may drift 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 with a teleoperation system similar to the experimental system depicted in Fig. 6. The HSI and 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 $b_{hu} = 1$Ns/m, spring $k_{hu} = 1000$Ns/m), and in addition applies a sinusoidal force with a frequency of 2 rad/s and an amplitude of 100N. The environment is given by a spring-damper system (damping $b_e = 1$Ns/m, spring $k_e = 10$N/m). The value of the relative deadband is set to $\epsilon = 0.20$.

The effect of the deadband control and the data reconstruction algorithms is shown in Fig. 3. With increasing velocity magnitude the size of the deadband increases. Depending on the sign of the force the passified HLS reconstructs the signal either at the lower or upper end of the deadband interval according to (9), observable in the switching signal in Fig. 3.

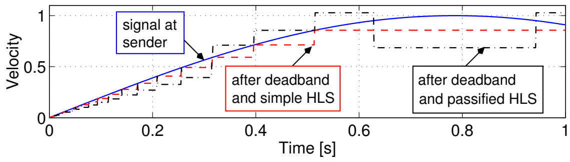

Fig. 3. Effect of deadband and data reconstruction

In Fig. 4 the computed energy balance of the communication subsystem (2) is shown for the simple and the passified HLS algorithm. The negative values for the simple HLS correspond to energy generation, hence non-passivity.The positive values for the passified HLS indicate energy dissipation, validating this approach.

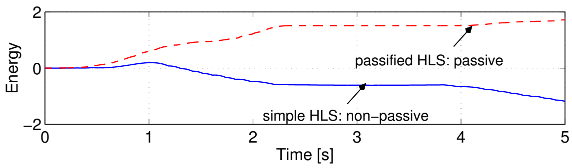

Fig. 4. Energy balance of the communication

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.

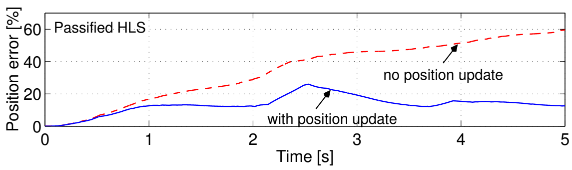

Fig. 5. Normed position error

4. PSYCHOPHYSICAL EXPERIMENTS

Psychophysical experiments were conducted in order to find an appropriate value for ϵ in (3). In this study the relative deadband is set equal 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.

4.1 Experimental Setup

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 and data reconstruction are implemented. The control loops operate at a sampling rate of 1000Hz representing the standard packet rate without deadband control.

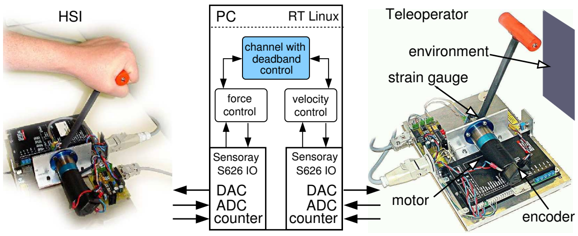

Fig. 6. Experimental setup

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. Only in of the three intervals, which was randomly determined the deadband algorithm with a certain value ϵ was applied, the other two were without deadband control. 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 same procedure as before was applied. 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.

4.3 Experimental Results

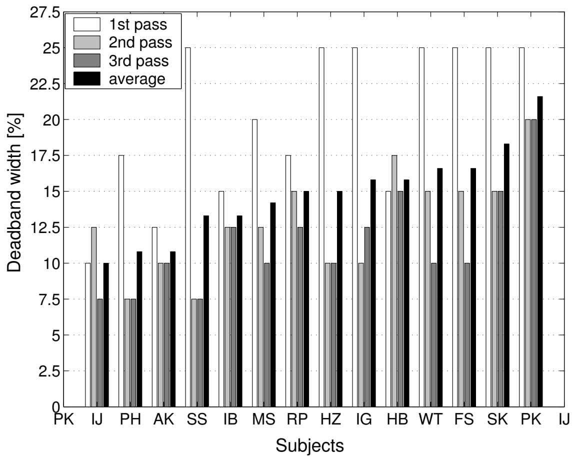

Fig. 7. Overview of the subjects' results

The specific results for every subject, see 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%. 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 relative 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 $\epsilon = 10\%$).

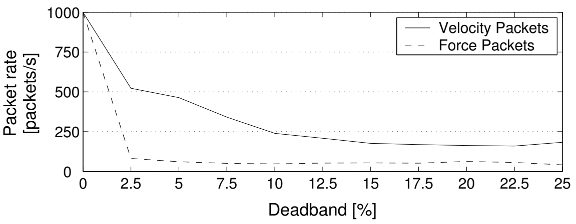

Fig. 8. Influence of the deadband width on packet rates

5. CONCLUSIONS

The proposed psychophysically motivated relative deadband control can significantly reduce (up to 85%) network traffic in a teleoperation system without impairing transparency. The data reconstruction by a passified "hold last sample" guarantees the stability of the teleoperation system. Psychophysical experiments are performed to validate the proposed approach. The presented algorithm is to the authors knowledge the first approach exploiting human haptic perception to reduce the data rate of haptic information.

ACKNOWLEDGEMENT

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