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Transparent Data Reduction in Networked Telepresence and Teleaction Systems
Part II: Time-Delayed Communication

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Transparent Data Reduction in Networked Telepresence and Teleaction Systems

Part II: Time-Delayed Communication

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Abstract

Two of the major challenges in networked haptic telepresence and teleaction systems are the time delay associated with the data transmission over the network and the limited communication resources. Sophisticated control methods are available for the stabilization in the presence of time delay. The reduction of haptic network traffic, however, is only poorly treated in the known literature. Data reduction approaches for

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time delayed haptic telepresence are not available at all. This article presents a novel approach to reduce the network traffic in haptic telepresence systems with constant (unknown) time delay. With the proposed deadband control approach data are sent only if the signal to transmit changes more than a given threshold value. In order to guarantee stability with time delay and data reduction a well-known time delay approach, the scattering transformation, is extended. Experimental user studies show that an average network traffic reduction up to 96% is achieved without significantly impairing the perception of the remote environment compared to the standard approach with time delay.

1 Introduction

Stability and transparency - in the sense that the human operator cannot distinguish between tele- and direct interaction - are the major goals for networked haptic telepresence systems control design. Without appropriate control measures inevitable network induced communication effects (time delay, packet loss, etc.) degrade transparency and may even destabilize the system. For example, data transmission over real communication channels is always affected by time delay ranging from some milliseconds to several seconds, e.g. in space applications. In addition to that, limited communication resources play a major role. Communication constraints are possibly imposed by communication technology, e.g. underwaterr and in space, but also in IP (Internet protocol) based networks where high data packet rates as they occur in haptic telepresence systems are hard to maintain (Mahlo, Hoene, Rosami, & Wolisz, 2005). For a deeper discussion on communication constraints and the network traffic characteristics of haptic telepresence systems refer to the companion article (Hirche, Hinterseer, Steinbach, & Buss, 2007). In summary, the major control challenges for networked haptic telepresence systems induced by the communication are: 1) time delay due to data transmission, 2) limited communication resources, and 3) loss of data. Sophisticated stabilizing control methods have been developed in the past for time delay (Anderson & Spong, 1989; Niemeyer & Slotine, 1991; Kosuge et al., 1996; Niemeyer & Slotine, 1998; Yokokohji, Imaida, & Yoshikawa, 2000; Lozano, Chopra, & Spong, 2002; Munir & Book, 2002, 2003; Stramigioli, 2002) and the data loss problem (Secchi, Stramigioli, & Fantuzzi, 2003; Berestesky, Chopra & Spong, 2004; Hirche & Buss, 2004; Yokokohji, Tsujioka, & Yoshikawa, 2002). The challenge of limited communication resources is poorly treated in the known telepresence literature. To the best knowledge of the authors no approach exists for the joint challenges of limited communication resources and constant time delay, which is subject of this article.

In the companion article (Hirche et al., 2007) a novel approach to reduce data traffic in haptic telepresence systems *without* time delay is introduced. The proposed deadband control aims at reducing the number of transmitted data packets. This is in contrast to the few works on compression of haptic data (Shahabi, Ortega, & Kolahdouzan, 2002; Ortega & Liu, 2002; Kron, Schmidt, Petzold, Zäh, Hinterseer et al., 2004; Borst, 2005) where primarily packet data load reduction is targeted through quantization and prediction schemes. Due to the haptic network traffic characteristics the reduction of the haptic data load only, however, has no significant influence on the network traffic load itself. For stability and performance reasons of the local control loops at human system interface (HSI) and teleoperator, data is sampled at high rates of 1000 Hz. Every single sample is sent in an individual data packet in order to prevent additional time delay from packetization. In current realizations, the network traffic portion induced by the protocol overhead is larger than the portion induced by haptic data. As a result, the reduction of the packet rate is more efficient than of the haptic payload data with respect to overall haptic data traffic reduction. A more detailed discussion on this topic is presented in the companion article (Hirche et al., 2007).

The main contribution of this article is a novel control approach to significantly reduce the network traffic induced by time-delayed haptic feedback systems without noticeable effect on the perceived transparency compared to the purely time-delayed case. The deadband control approach introduced in (Hirche et al., 2007) for haptic telepresence systems *without* time delay is extended here to the *constant* (unknown) time delay case. Data is sent only if the difference between the current and the most recently sent value exceeds a certain threshold. Without communication time delay the velocity of the HSI can directly be communicated as command signal to the teleoperator while the measured interaction force with the remote environment is fedback to the HSI without stability problems. In consequence, deadband control is directly applied to velocity and force signals. However, with this architecture even a small time delay destabilizes the haptic telepresence system. The well-known scattering transformation approach stabilizes for unknown constant time delay. This approach is extended here in order to stabilize the haptic telepresence system with *constant (unknown) time delay and deadband control*. No longer the velocity and force signals, but linear combinations of them called scattering (wave) variables are transmitted over the communication network with the dDeadband control applied to them. Two deadband types are compared: a constant deadband and a relative deadband. In the latter strategy the deadband width linearly depends on the magnitude of the transmitted signal (scattering/wave variables) while it is constant in the former. The constant deadband approach performs better, i.e. achieves larger network traffic reduction at the same transparency level. This is validated in experimental user studies with a one degree-of-freedom telepresence system. The impact of deadband control on network traffic reduction is studied. The induced network traffic is measured during the experiments to evaluate the effect on network traffic reduction. A significant average network traffic reduction up to 96% is achieved in these experiments.

The remainder of this article is organized as follows: The deadband control principle is introduced in Section 2, followed by the introduction of the control systems architecture including the stabilizing measures and a transparency discussion in Section 3 and the experimental user study in Section 4.

2 Deadband Control

In a haptic telepresence system the human operator moves the HSI to command the motion of the teleoperator. The HSI motion is measured in equidistant time intervals, typically every millisecond, to ensure stability of the local control loop. The HSI motion signal is communicated to the teleoperator where local control loops ensure that the teleoperator follows the motion of the HSI. The teleoperator measurements, e.g., the environment interaction force, is communicated back to the HSI where it is displayed to the human operator.

Without deadband control *every* measurement is sent in an individual data packet, i.e. data packets are sent forth and back at the local sampling rate of the measurements resulting in a high packet rate of approximately 1000 packets/s. This is visualized in Figure 2 of the companian article (Hirche et al., 2007).

With deadband control, measurements are sent over the communication network only if the difference between the current measurement and the most recently sent value exceeds a certain threshold, the deadband width. Consequently, data packets are no longer transmitted in equidistant time intervals. The approach obviously leads to a reduction of the number of transmitted packets; in fact, if the signal to be transmitted is constant over a time interval, then no data is transmitted at all.

Without time delay as considered in the companian article (Hirche et al., 2007), the deadband is directly applied to velocity and force signals with a relative deadband, i.e. the deadband width linearly increasing with increasing signal magnitude. Motivation for the relative deadband choice is the fact that the discrimination threshold for haptic stimuli behaves approximately according to Weber's law (Weber, 1851), i.e. linearly increases with stimulus intensity (Burdea, 1996). In order to stabilize the system with constant time delay linear combinations of velocity and force, the so-called scattering (wave) variables, are transmitted over the communication network. The scattering transformation approach is explained in Section 3.1. The psychophysical motivation of using a relative deadband is no longer justified for the time delay case with the deadband applied to the scattering variables. The question is, which deadband type is optimal in the sense of minimal network traffic while guaranteeing a certain level of transparency or alternatively maximizing transparency for a given network traffic reduction. In this work the constant and the relative deadband approach are investigated for their influence on transparency and network traffic reduction.

2.1 Constant and Relative Deadband

The deadband controller compares the most recently sent value $u(t')$ with the current value $u(t)$, $t > t'$. If the absolute value of the difference $|u(t') - u(t)|$ is smaller than the absolute deadband width $\Delta_{u(t')}$ then no update is sent over the network. Otherwise the value $u(t)$ is transmitted and a new deadband is established around this just transmitted value.

In case of the constant deadband the absolute deadband width does not depend on the signal and $\Delta_{u(t')} = \Delta_c$ holds with Δ_c the constant deadband width. The relative deadband grows linearly with the magnitude of the value $u(t')$. With the proportional factor ε the absolute value $\Delta_{u(t')}$ of the deadband is defined by $\Delta_{u(t')} = \varepsilon|u(t')|$. If the signal $u(t')$ is close to the origin the deadband becomes infinitely small. For practical application the deadband is lower bounded by $\Delta_{u(t')} \geq \Delta_{\min}$. The value $\Delta_{\min}$ can be tuned such that the number of transmitted packets is insensitive to measurement noise.

3 Control System Architecture

The control system architecture to stabilize the haptic telepresence system with time delay and deadband control is introduced in the following. Therefore the widely used stabilizing control architecture for time delay, the scattering transformation, is reviewed and extended to stabilize with constant time delay and deadband control.

3.1 Stability with Time Delay

A control loop is closed over the communication network through the forward and backward communication of haptic data. The data transmission inevitably takes a certain amount of time introducing a time delay into the closed control loop. It is well-known that even small time delay destabilizes the haptic telepresence system. A widely used approach for the stabilization of haptic telepresence systems in the presence of time delay is the scattering transformation (Anderson & Spong, 1989; Niemeyer & Slotine, 1991). No longer the velocity and force signals itself, but linear combinations of these data called scattering variables are transmitted over the communication network

$$
\begin{aligned}
u_l &= \frac{1}{\sqrt{2b}}(f_h^d + b\dot{x}_h)\,; \qquad & u_r &= \frac{1}{\sqrt{2b}}(f_e + b\dot{x}_t^d)\,; \\
v_l &= \frac{1}{\sqrt{2b}}(f_h^d - b\dot{x}_h)\,; \qquad & v_r &= \frac{1}{\sqrt{2b}}(f_e - b\dot{x}_t^d)\ ,
\end{aligned}
\tag{1}
$$

where $\dot{x}_h$ represents the HSI velocity, $\dot{x}_t^d$ the desired teleoperator velocity, f_e the environment interaction force, and f_h^d the desired force to be displayed by the HSI; $b > 0$ is a tunable parameter called characteristic impedance. The scattering variables u_l (forward path) and v_r (backward path) are transmitted over the communication network and arrive at the corresponding receiver with the time delay T

$$
u_r(t) = u_l(t-T); \qquad v_l(t) = v_r(t-T), \tag{2}
$$

see also Figure 1 for visualization. Note, that all the following considerations also apply for different but constant delays in the forward and backward path. For ease of notation they are assumed to be equal in the remainder of this article. The basic architecture is depicted in Figure 1, the data reconstruction block is discussed in the following.

Figure 1 here.

3.2 Stability with Deadband Control

As previously discussed, the deadband-based data reduction approach reduces the number of packets being sent. The transmission of fewer data packets itself does not have an effect on the stability of the haptic feedback system. However, at each receiver side the local control loops still operate at the high constant sampling rate. Accordingly, updates of the current measurement are required in each sampling instant. Due to the deadband control, however, these measurements are not available at *every* sampling time instant, but only if a data packet has been transmitted. The missing measurements have to be reconstructed as indicated by the data reconstruction block in Figure 1. Note that the deadband control and as such the data reconstruction apply to the scattering variables Eq. (1). The reconstruction can be formally described by the reconstruction operator, here exemplarily for the forward path using Eq. (2)

$$u_r(t) = \begin{cases} u_l(t^* - T) = u_l(t') \text{ if } t = t^* \\ \zeta(u_r(t^*), t) \quad \text{otherwise,} \end{cases} \tag{3}$$

where it is assumed that the most recent data u_r arrived at time $t^* = t' + T$; $\zeta(\cdot)$ denotes the reconstruction algorithm. Known transparent extrapolation strategies such as ARMA algorithms (Hirche & Buss, 2004) may generate or dissipate energy depending on the signal behavior. As the signal behavior is not known in advance, there is the chance of energy generation associated with potential destabilization of the system by the use of such an algorithm. A reconstruction algorithm that guarantees stability has been developed in (Hirche, 2005) and is briefly introduced in the following.

3.2.1 Energy Supervised Data Reconstruction The underlying idea is to observe the energy balance of the communication subsystem including data reconstruction online; similar ideas of energy monitoring have been applied for the case of time-varying delay (Niemeyer & Slotine, 1998, Yokokohji et al., 2000) and packet loss (Yokokohji et al., 2002). As the standard case a transparent, but potentially energy generating reconstruction strategy ζ_{np} is applied. If the energy generation exceeds some pre-specified value (zero in the general case), however, the reconstruction algorithm is switched to a more conservative, energy dissipating algorithm ζ_p. Formally, the reconstruction algorithm ζ

in Eq. (3) with energy supervision is defined by

$$\zeta(u_r(t^*), t) = \begin{cases} \zeta_{np}(u_r(t^*), t) & \text{if } E_v(t) \geq 0 \\ \zeta_p(u_r(t^*), t) & \text{otherwise,} \end{cases} \tag{4}$$

where $E_v(t)$ represents the observed energy balance of the forward or backward communication path. A positive value indicates that there has been more energy dissipated than generated in the communication subsystem in the past. Potential temporal energy generation of the transparent reconstruction algorithm ζ_{np} can be compensated by the amount of formerly dissipated energy. The value of the energy balance $E_v(t)$ of the forward path is computed at the receiver side

$$E_v(t) = \int_0^{t'} u_l^2 \,\mathrm{d}\tau - \int_0^{t} u_r^2 \,\mathrm{d}\tau.$$

The lefthand integral term represents the input energy to the forward path up to the most recent transmission time instant t', the righthand integral term is the output energy of the forward path including the data reconstruction up to the current time t. Additionally to the value u_l also the input energy, computed at the sender side, has to be transmitted. The basic principle of the energy supervised data reconstruction is visualized in Figure 2. It replaces the gray colored blocks in Figure 1. For more details including the stability proof of this reconstruction concept please refer to (Hirche, 2005).

Figure 2 here.

3.2.2 Reconstruction Algorithms

Any extrapolation algorithm can be applied as reconstruction algorithm ζ_{np} in Eq. (4). In the subsequent experimental study a Hold-Last-Sample (abbreviated by HLS, also called zero-order-hold) is used, being the most common reconstruction algorithm in sampled data systems. The value $u_r(t^*)$ of the most recently arrived packet is held until a new packet arrives

$$\zeta_{np}(u_r(t^*), t) = u_r(t^*), \tag{5}$$

where t^* is the time instant when the most recent packet arrived and $t > t^*$ the current time. See Figure 3 (a) for a visualization for an example signal. The HLS algorithm introduces a comparably low distortion but potentially generates energy (Hirche, 2005). An energy dissipating reconstruction algorithm ζ_p for application in the energy supervised reconstruction strategy Eq. (4) is proposed in the following. Setting the value to zero, if no data packet arrives at the receiver side, is a simple dissipative reconstruction strategy used for the packet loss case in (Hirche & Buss, 2004). For deadband control it is overly conservative: Assuming no packet loss, if no data packet arrives at the receiver at the time t, then the data value at the sender $u_l(t-T)$ and as such the current value $u_r(t)$ at the receiver must lie within the deadband interval $\Delta_{u_l(t')}$ of the most recently received value $u_r(t^*) = u_l(t')$

$$|u_r(t^*)| - \Delta_{u_l(t')} \leq |u_r(t)| \leq |u_r(t^*)| + \Delta_{u_l(t')},$$

A modified HLS is proposed

$$\zeta_p(u_r(t^*), t) = u_r(t^*) - \text{sign}\{u_r(t^*)\}\Delta_{u_l(t')}, \tag{6}$$

reconstructing the missing data at the lower (in an absolute sense, i.e. closer to the origin) end of the current deadband interval, see Figure 3 (b) for a visualization. The modified HLS algorithm can be interpreted as a worst case estimation of the untransmitted data corresponding to a minimal wave input energy assumption. With this data reconstruction algorithm the communication subsystem dissipates energy, see (Hirche, 2005) for a proof.

In the following, the energy supervised reconstruction strategy Eq. (4) with the HLS as possibly energy generating algorithm ζ_{np}, and the modified HLS as strictly dissipating algorithm ζ_p is applied, see Figure 3 (c) for visualization.

Figure 3 here.

3.3 Transparency

The level of transparency in the networked haptic telepresence system depends on the value of the communication time delay T and of the deadband parameter, Δ_c for the constant deadband and ε for the relative deadband. With increasing values transparency deteriorates more and more while network traffic is decreased. The influence of time delay and deadband control on transparency is discussed in the following. As transparency criterion the comparison of the impedance Z_h displayed to the human and the environment impedance Z_e is applied. The mechanical impedance is defined as the mapping from velocity v to force f and is for the linear time-invariant case represented by the transfer function $Z(s) = f(s)/v(s)$ where s is the Laplace variable. Ideal transparency is achieved if $Z_h = Z_e$ (Lawrence, 1993).

3.3.1 Transparency with Constant Time Delay Time delay distorts the displayed impedance Z_h, ideal transparency is not achievable. Using the scattering transformation with the characteristic impedance b as stabilizing control measure, the influence of the roundtrip time delay on the displayed impedance is as follows (Hirche & Buss, 2006):

- In *free space motion* ($Z_e = 0$) an inertia is displayed, i.e. $Z_h(s) = m_h s$, with the inertia linearly depending on the time delay as $m_h = \frac{1}{2} b T_{rt}$.

- A *stiff wall* ($Z_e = k_e/s$) is displayed softer at higher time delay. The stiffness coefficient of the displayed impedance $Z_h = k_h/s$ becomes smaller with increasing time delay according to $\frac{1}{k_h} = \frac{1}{k_e} + \frac{T_{rt}}{2b}$.

The characteristic impedance b can be tuned such that for a given time delay the displayed impedance is within the discrimination threshold range of the environment impedance (Hirche & Buss, 2006), i.e. such that the environment impedance is still *perceived as transparent*. However, free space motion requires a very small value of b while for transparent perception of a stiff wall the parameter must be large. Typically, a compromise value is chosen.

3.3.2 Transparency with Deadband Control With deadband control the transmitted signals, the scattering variables, are distorted. Psychophysical insights lead to the choice of a relative deadband in the companian article (Hirche et al., 2007) where velocity and force signals are transmitted in the telepresence system without time delay. Such insights are not available for the perception of scattering variables. In consequence, the choice of the deadband type is not straightforward. Here the relative and constant deadband approach are investigated for their influence on the displayed impedance using a cross correlation analysis to identify the displayed impedance. In Figure 4 the Bode plots of the displayed impedance with constant and relative deadband control for the same network traffic reduction by 68.5% are compared to the case without deadband and the environment impedance. The difference between environment impedance and the displayed impedance without deadband is caused by the time delay, observe the reduced stiffness at the already very small time delay value of only $T = 1\,\mathrm{ms}$. With the constant deadband approach a stiff wall is displayed softer, similar to the effect of time delay. With the relative deadband approach the displayed impedance largely differs from the environment impedance, and also from the displayed impedance without deadband control. In fact, no longer a stiffness is displayed: The stiffness property, which is observable from the -20dB/decade falling magnitude plot at low frequencies, vanishes. That indicates that the constant deadband approach is more transparent than the relative deadband approach for the same network traffic reduction.

Figure 4 here.

4 Experimental User Study

Generally, high transparency and low network traffic are contradicting design goals. Within the deadband control approach, low network traffic is achieved by a high deadband width, which in turn results in high signal distortion at the receiver side and therefore low transparency. Considering the limits of human haptic perception, however, the slight distortion due to deadband control is not necessarily perceived. Transparency is additionally deteriorated by the time delay in the communication as discussed in Section 3.3.1.

The goal of the following experiments is to study the effect of deadband control on the network traffic reduction. The constant and the relative deadband approach are compared. The maximal deadband parameter values Δ_c and ε are determined such that the difference to the purely time delayed case without deadband control is not perceivable.

4.1 Experimental Apparatus and Conditions

The experimental hardware consists of two identical 1-DOF haptic devices connected to a PC as presented in Figure 5, for more technical details see companian article (Hirche et al., 2007), Section 4.1. Here in addition to the local control algorithms for HSI and teleoperator, the communication subsystem is composed of MATLAB/SIMULINK blocksets; standalone realtime code for RT Linux is automatically generated from that. The communication subsystem, shown in Figure 5, consists of the communication line with the constant time delay, the deadband control, see Section 2, the energy supervised data reconstruction algorithm as described in Section 3.2 and the scattering transformation Eq. (1). The time delay in the forward and backward path is set to $T = 50\,\mathrm{ms}$, i.e. the round-trip time delay is $T_{\mathrm{rt}} = 100\,\mathrm{ms}$; the characteristic impedance to $b = 25\mathrm{Ns/m}$. The control loops operate at a sampling rate of 1000Hz representing the standard packet rate without deadband control. The deadband control and the data reconstruction strategy are equally applied with the same deadband value in the forward and the backward path. The lower bound for the relative deadband is set to a small value of $\Delta_{\min} = 0.002\,\sqrt{\mathrm{W}}$ such that measurement noise has no influence, see Section 2.1.

Figure 5 here.

4.2 Procedure

Altogether 11 subjects were tested (3 female, 8 male, aged 22–30, 2, namely S4 and S11, with prior contact to the experimental setup). None of the subjects had any impairments of sensorimotor capabilities. The subjects were not reimbursed. The subjects were told to operate with their preferred hand. They were equipped with earphones to mask the sound the device motors generate. The subjects were provided with visual feedback. During a familiarization phase subjects were told to feel operation in free space and in contact with a stiff wall without deadband control. As soon as they felt familiar with the system the measurement phase began. The subjects were told what the effect feels like and that it is best detected through varying the applied force in contact.

In the experiment detection thresholds for the deadband parameters $\Delta_c(\varepsilon)$ were determined using a three interval forced choice (3IFC) paradigm. The subjects were presented three consecutive intervals of 20 seconds, in one randomly chosen with deadband control applied, all three with the same constant time delay. For more details on the procedure refer to Section 4.2 in the companian article (Hirche et al., 2007). The experiment started with an initial deadband parameter $\Delta_c = 0.045\,\sqrt{\mathrm{W}}$ ($\varepsilon = 2\%$) and was increased after every incorrect answer by the same values. After three completed passes the subjects where asked in which environment condition they most likely felt the difference with the choices a) free space motion, b) contact with the wall, c) both.

4.3 Results

Figure 6 here.

The specific situation that accounted for the detection has been reported by the subjects as follows: a) free space motion: by five subjects, b) contact with the wall: by four subjects, and c) both: by two subjects. This result indicates that no specific situation accounts for the detection.

The specific results for the detected deadband values for every subject in the three passes are presented in Figure 6 (a) for the constant deadband, and in Figure 6 (b) for the relative deadband. They range from $0.09\sqrt{\mathrm{W}}$ to $0.5\sqrt{\mathrm{W}}$ for the constant, and from 6% to 28% for the relative deadband. The average and standard deviation over all subjects and all passes is $\bar{\Delta}_c = (0.28 \pm 0.07)\sqrt{\mathrm{W}}$, and $\bar{\varepsilon} = (14.7 \pm 5.5)\%$[1].

During the experimental user study the network traffic volume was recorded. The mean percentage of transmitted packets along with the standard deviation is depicted as a function of the deadband parameter in Figure 7 (a) for the constant, and in Figure 7 (b) for the relative deadband approach (100% represent the standard approach with 1000 packets/s in the forward and the backward path, respectively). As expected, larger deadbands lead to higher traffic reduction, on average as well as in the standard deviation. At higher deadband parameter values an asymptotic behavior of the transmitted packet number is observable. The number of transmitted packets for the deadband parameters, its average values and its standard deviation are presented in Table 1. Note, that on average only 4% of the original numbers of packets are transmitted (corresponds to 40 packets/s) for $\Delta_c = 0.21\sqrt{\mathrm{W}}$ in the constant deadband case, and 10% for $\varepsilon = 9.2\%$ in the relative deadband case. This corresponds to an average network traffic reduction by 96% and 90%, respectively. Observe that even for the smallest in a pass detected deadband value of $0.09\sqrt{\mathrm{W}}$ (6%) the network traffic reduction is substantial with 90% (86%).

Figure 7 here.

[1]The determination of the deadband detection threshold using adaptive procedures with more subjects, also for independent deadband control in the forward and the feedback, is topic of a forthcoming paper.

4.4 Discussion

A major network traffic reduction is achievable by applying deadband control (deadband on scattering variables) without noticeably deteriorating the perception of the remote environment. The constant deadband control approach performs better than the relative deadband approach. This result, obtained from the analytic transparency analysis, is clearly validated in the experimental user study. There are a number of factors that additionally may play a role for the transparent network traffic reduction, some of them possibly further improve the result:

- Only a constant and a relative deadband are investigated here. Other (e.g. non-linear) deadband types might be beneficial, too.
- The deadband detection thresholds were determined here for a fixed round-trip time delay T_{rt}. The time delay together with the scattering transformation has a significant influence on the transparency as discussed in Section 3.3.1. The time delay and the characteristic impedance b may have an influence on the network traffic reduction.
- The deadband parameters in the forward and the backward communication path are equal in this study. Considering the asymmetry in the human haptic ac-

Table 1: Transmitted packet number.

	Constant deadband Δ_c in $\sqrt{\mathrm{W}}$			Relative deadband ε in %		
	0.21	0.28	0.35	9.2	14.7	20.2
Transmitted packets in %	4	3	2.5	10	7	6

tion/perception, different parameters may even increase the efficiency of the proposed approach.

- Further improvement is expected if the position additionally to the velocity is transmitted (Chopra, Spong, Hirche, & Buss, 2003; Chopra, Spong, Ortega, & Barabanov, 2004), see also discussion in the companian article (Hirche et al., 2007).

In summary, the deadband control approach is very promising with respect to a transparent network traffic reduction in haptic telepresence systems with time delay. Observe that the reported network traffic reduction is an average value. Deadband control provides strict communication rate guarantees only in terms of the sampling rate which is the maximum possible packet rate. The maximum packet rate occurs at sudden changes of the scattering variables, i.e. of force and/or velocity, e.g. in the transition from free space motion to contact.

5 Conclusions and Future Research

This article presents a novel approach for network traffic reduction in haptic telepresence systems with constant (unknown) time delay. With the proposed deadband control a packet containing haptic data is transmitted only if the signal has changed more than a threshold value, the deadband width. Stability is guaranteed by the well-known scattering transformation and appropriate data reconstruction at the receiver side. It is shown that the constant deadband approach outperforms the relative deadband approach. This is validated in experimental user studies with a one degree-of-freedom telepresence system where deadband parameter detection thresholds are preliminarily determined. Experimental results show that a major network traffic reduction up to 96% is achieved without significantly degrading the perception of the remote environment compared to the time-delayed case. Future work includes the analysis of the time delay influence on the network traffic reduction and the extension of the approach to multi-degree-of-freedom telepresence systems. A unified framework for haptic data reduction and transmission is a midterm goal, longterm goal is an integrated approach to data transmission in networked multimodal telepresence and teleaction systems.

Acknowledgment

The helpful and constructive comments by the anonymous reviewers are highly appreciated. The authors gratefully acknowledge the experimental support by Andrea Bauer. This work was supported in part by the German Research Foundation (DFG) within the Collaborative Research Centre SFB 453 on "High-Fidelity Telepresence and Teleaction".

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Figure Captions and Size of Figures

Figure 1: Deadband controlled haptic telepresence system with time delay.

(width = 1 column)

Figure 2: Energy supervised data reconstruction.

(width = 1 column)

Figure 3: Reconstruction algorithms: (a) HLS Eq. (5), (b) modified HLS Eq. (6), and (c) energy supervised reconstruction Eq. (4) with ζ_{np} = HLS and ζ_p = modified HLS. For clarity the reconstructed signal is depicted without time delay; in case of time delay it would be shifted to the right by the time delay.

(width = 2 column)

Figure 4: Bode plot of displayed impedance Z_h shows influence of deadband type: with relative deadband no stiffness displayed when environment is stiff, with constant deadband stiff environment is displayed as stiffness, but slightly softer.

(width = 1 column)

Figure 5: Experimental apparatus: a one degree-of-freedom haptic telepresence system.

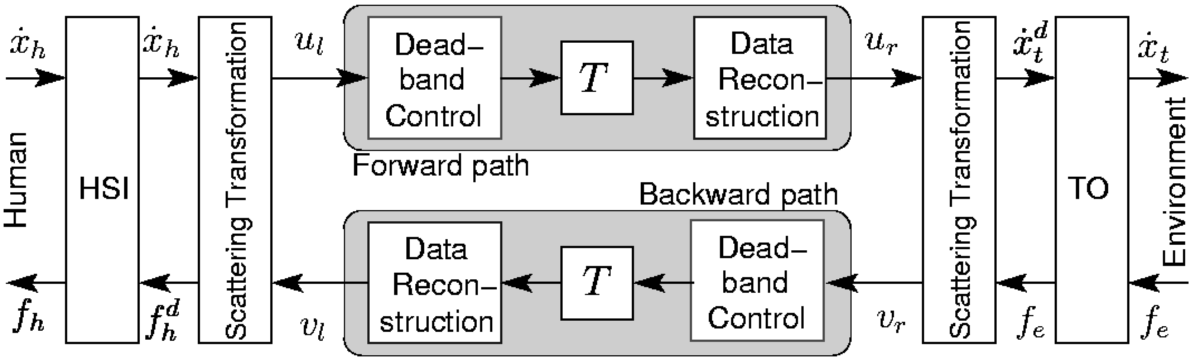
(width = 1 columns)

Figure 6: Subjective evaluation results: (a) constant deadband, (b) relative deadband.

(width = 2 columns)

Figure 7: Network traffic reduction by deadband control: Average number of transmitted packets and standard deviation as a function of the deadband parameter for constant deadband (a) and relative deadband (b); 100 % correspond to 1000 packets/s.

(width = 2 columns)



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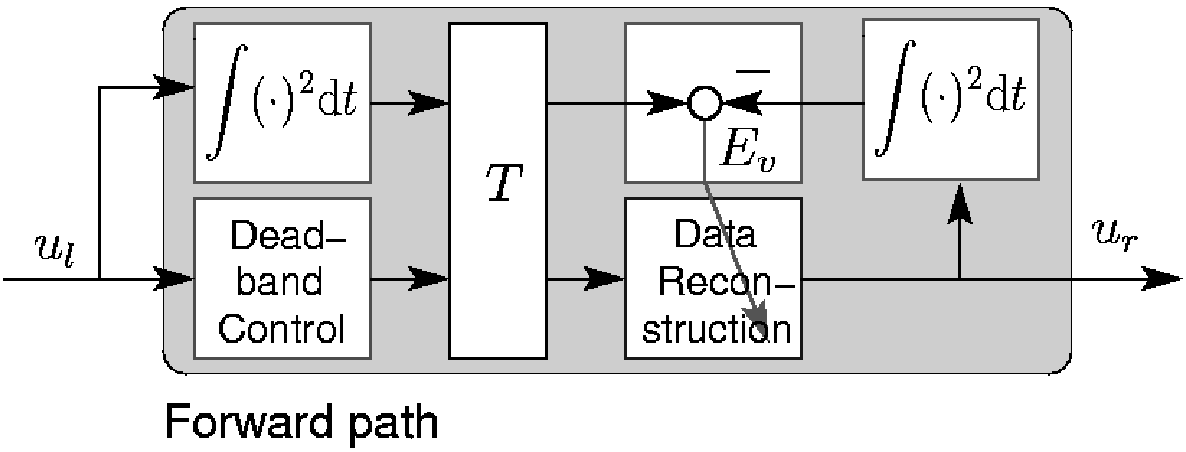
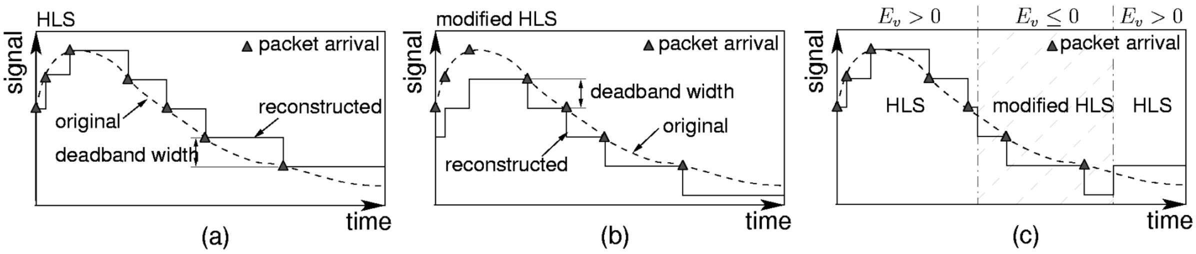


Figure 2: *Energy supervised data reconstruction.*



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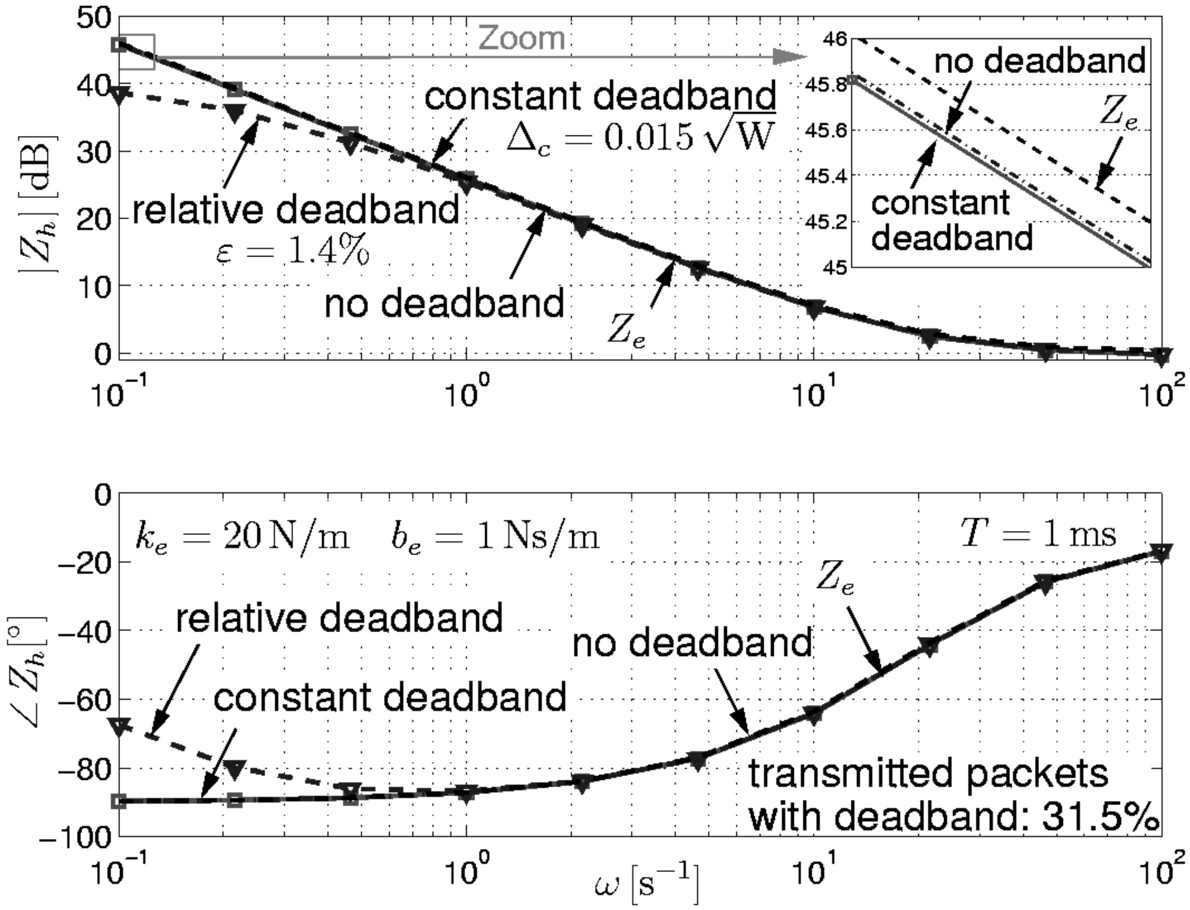

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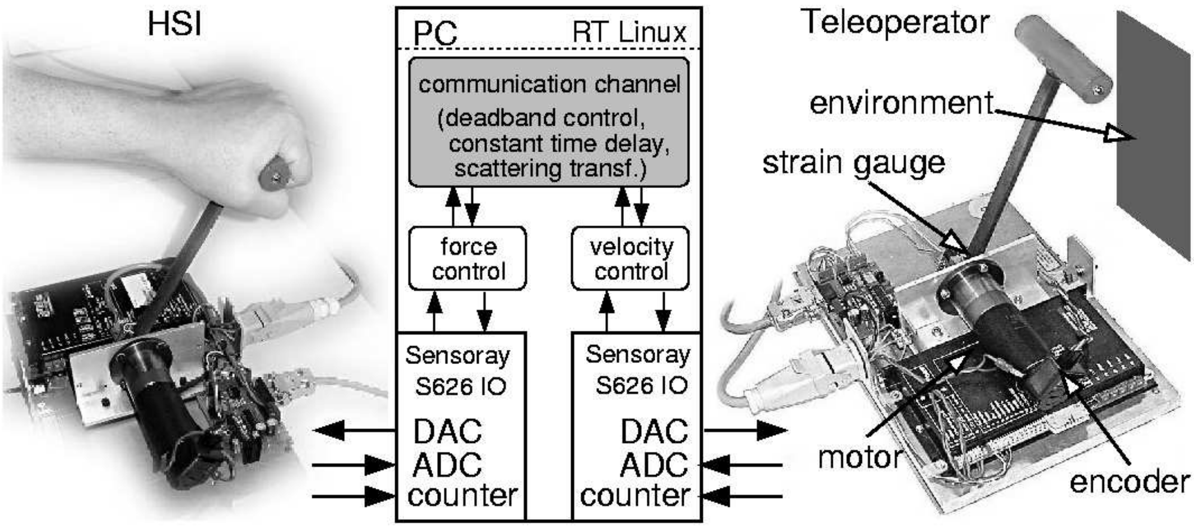

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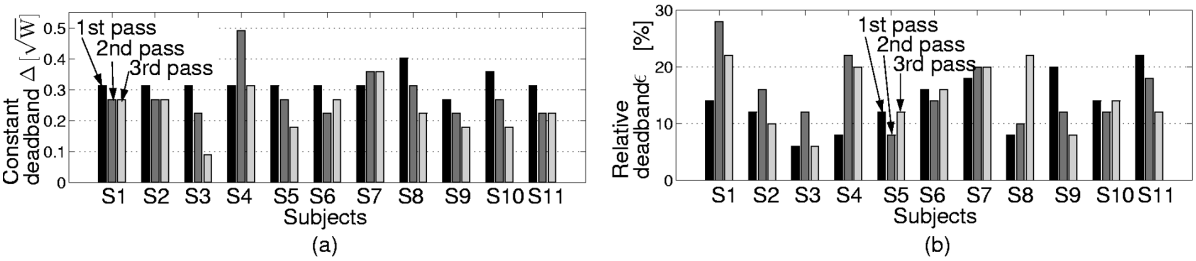

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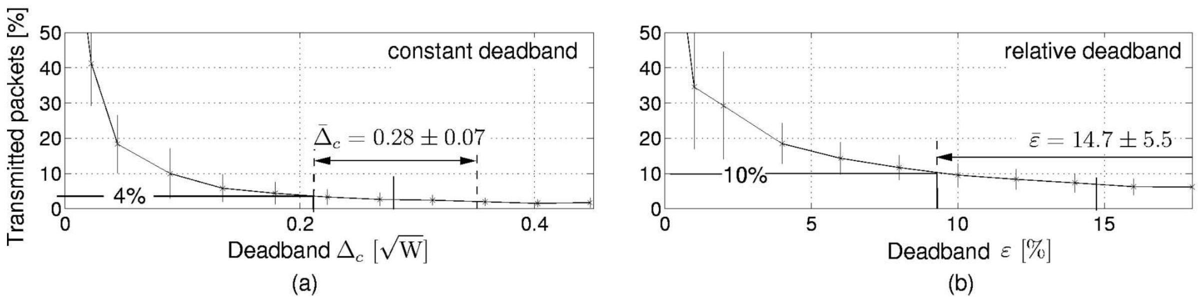

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