Human Perception Oriented Control Aspects of Networked Telepresence and Teleaction Systems

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Abstract: Multimodal telepresence and teleaction systems enable a human operator to perform in remote environments through a telerobot and a communication network. From a control point of view, the networked force feedback control system is the key challenge. This paper discusses human perception oriented aspects for the analysis and synthesis of telepresence control architectures. Based on human perception insights several facts how communication time delay distorts the perceived environment characteristics are studied. A psychophysically motivated deadband control approach for network traffic reduction up to 87% is discussed with the deadband threshold parameter being determined in psychophysical experiments.

Keywords: Teleoperation, Communication Networks, Deadband, Human Perception.

1. Introduction

In a multimodal telepresence and teleaction (TPTA) system, also called teleoperation system, a human operator commands a remote robot (teleoperator) by manipulating the human system interface (HSI). Sensors at the telerobot measure environment interaction, which are then communicated and fed back to the human operator using the corresponding multimodal HSIs, see Fig. 1. Application areas of TPTA technology reach from tele-surgery, -maintenance to tele-training and -entertainment, see e.g. [1] for an overview. The focus of this paper is on the haptic (force) feedback system forming a closed-loop control system over a communication network, e.g. the Internet, the human operator and the generally unknown remote environment.

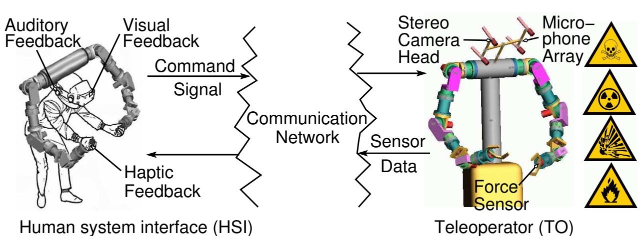

Figure 1: Multimodal telepresence and teleaction system.

In order to guarantee stability with time delay the passivity concept using the scattering transformation [2], equivalently the wave variable transformation [3], is employed, where velocity and force signals are exchanged between the HSI and the teleoperator. Transparency – in the sense that the technical systems and communication network should not be felt by the human operator, i.e. the operator should feel as if directly being present and active in the remote environment – is one of the key challenges in TPTA systems. Perfect transparency from the engineering point of view is difficult to achieve in real systems. However, such a technically non-transparent system may still appear transparent to the human due to human haptic perception limits. Hence, the consideration of human haptic perception is an important issue for the analysis and synthesis of networked TPTA system control architectures.

In this paper the transparency aspects of TPTA systems with time delay are discussed from a human perception point of view. Therefore the known perception thresholds (just noticable difference, JND) for mechanical parameters such as stiffness are considered. Further, a novel method for communication bandwidth reduction is discussed based on psychophysical insights of human perception. Usually, the control loop closed over the communication network is operated at a sampling rate above 500 Hz, which results in high packet rates in a packet switched network. Such high rates result in congestion of the network and thus can cause higher transmission delay and packet loss. Therefore in [4] a deadband control approach [1] is introduced exploiting the fact that the human is not able to detect arbitrarily small differences in velocity and force signals, see e.g. [5, 6]. The goal is to reduce the network traffic without impairing the transparency. Therefore, in this paper the deadband detection threshold is determined in psychophysical experiments. Similar control approaches have been proposed for the closely related NCS [7]. TPTA systems are in some sense a special case of NCS, although due to the human in the control loop additional challenges regarding stability and performance analysis and have to be faced.

The remainder of this paper is organized as follows: Section 2 presents the control and psychophysical background; Section 3 analyzes the transparency of the haptic feedback system with wave variable transformation and time delay; Section 4 proposes the human oriented deadband control approach; Section 5 determines the deadband threshold parameter from psychophysical experiments.

[1] The deadband control strategies have been developed in close collaboration with P. Hinterseer and E. Steinbach. This work is supported in part by the DFG Collaborative Research Center SFB453 and Technische Universität München.

2. Theoretical Background

A haptic feedback system consists of a force feedback capable HSI (variables indexed $_h$) and the teleoperator (index $_t$) interacting with an usually unknown remote environment (index $_e$) as shown in Fig. 2. In bilateral telepresence the human manipulates the HSI applying the force f_h. 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 sensed at the remote site, resulting from the interaction with the environment, is transmitted back to the HSI serving as reference signal f_h^d for the local force control. The time delays T_1, T_2 in the forward and backward path, respectively, see Fig. 2, are assumed to be constant. Without further control measures the system is unstable due to the time delay.

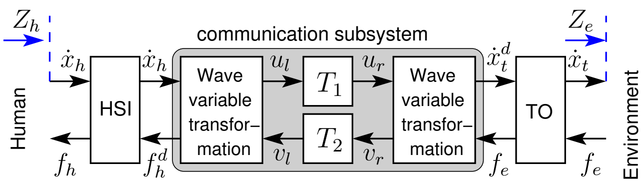

Figure 2: System architecture with wave variable transformation.

2.1 Stability by Passivity Approach

The passivity concept provides a sufficient condition for stability of the haptic feedback 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

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

holds, with $P_{in}(\tau)$ denoting the power input to the system, $\boldsymbol{u}(\tau)$, $\boldsymbol{y}(\tau)$ the input and output vector. In classical teleoperation architectures, as proposed in [2], the appropriately locally controlled HSI and teleoperator exchange velocity and force signals. As a result the teleoperator/environment and the human/HSI are considered passive subsystems. The wave variable transformation [2, 3] passifies the communication two-port for *constant* delays with the transformation equations

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

The tuning parameter b represents the wave impedance of the communication line.

2.2 Transparency and Haptic Perception

The design goal of the haptic feedback system is that the human operator cannot distinguish between direct interaction with an environment and teleoperated interaction with an remote environment. Then the 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 [8]; according to [9] transparency requires the equality of the impedance perceived by the human and the environment impedance

$$Z_h = Z_e, \qquad (3)$$

with the mechanical impedance Z defined as the mapping from velocity v to force f. In most cases the considered impedances can sufficiently well approximated by a LTI system; then the impedance can be represented by the transfer function $Z(s) = f(s)/v(s)$.

The transparency requirements are difficult to satisfy in a real system, especially with time delay. On the other hand, the knowledge of psychophysical effects in human haptic perception is not incorporated, i.e. the transparency requirements are overly strict in general.

According to numerous psychophysical studies the human being is only able to discriminate velocity and force changes which have a magnitude proportional to the signal value itself. The detection threshold, called *just noticable difference* (JND), for force perception with hand and arm is around 10% [5], for velocity around 8% [6]. Similar detection thresholds exist for the mechanical parameters such as inertia, damping and stiffness. The JND for stiffness perception, for instance, with fingers is around 8% [10], with hand and arm (cross-limb) 23% [11]. These results encourage the transparency analysis based on the mechanical parameters of the perceived impedance.

3. Transparency with Delay

In order to evaluate the influence of the communication delay on the perceived mechanical properties the perceived impedance Z_h is computed with the reformulated equations (2)

$$Z_h(s) = b\frac{1 + R\,e^{-sT}}{1 - R\,e^{-sT}} \quad \text{with} \quad T = T_1 + T_2. \qquad (4)$$

with

$$R = \frac{Z_e - b}{Z_e + b}. \qquad (5)$$

For vanishing delay $T = 0$ the perceived impedance is equal to the environment impedance. Note that for this analysis the dynamics of the teleoperator and the HSI are assumed to be negligible, such that the teleoperator/environment impedance is equal to the environment impedance Z_e, the impedance displayed to the HSI is equal to the impedance Z_h perceived by the human.

The main challenge for an intuitive physical interpretation of the perceived impedance is the complexity of its transfer function (4). Due to the delay element this transfer function has an infinite number of poles and zeros. Therefore the perceived impedance is approximated by a lower order system.

3.1 Low Frequency Approximation

The approximation of the perceived impedance transfer function is computed using a Pade series of finite order to approximate the delay transfer functions in (4). The order of the perceived impedance approximation depends on the order N of the Pade approximation. In order to simplify the analysis the delay elements are approximated by a first order Pade series

$$e^{-sT} \approx \frac{1 - \frac{T}{2}s}{1 + \frac{T}{2}s}. \tag{6}$$

Generally, a Pade approximation of order N is valid for frequencies $\omega < \frac{N}{3T}$, consequently, the first order approximation is valid for frequencies $\omega < \frac{1}{3T}$. Inserting (6) in (4) the approximated perceived impedance is computed by

$$Z_h(s) \approx b\frac{2Z_e + bTs}{2b + TZ_e s} \quad \text{for} \quad \omega < \frac{1}{3T}. \tag{7}$$

For further analysis this transfer function is splitted into a low frequency component F_{lf} and a high frequency component F_{hf} as follows

$$Z_h(s) \approx F_{lf}(s)\, F_{hf}(s) \quad \text{with } |F_{hf}(0)| = 1. \tag{8}$$

The component F_{lf} represents a good approximation of the low frequency behavior of the perceived impedance, its parameters can be derived analytically.

An analysis of the perceived impedance is exemplarily carried out in detail for the important case of contact with a stiff wall in the following.

3.2 Perceived Impedance for Still Wall Environment

In contact with a stiff wall a force proportional to the wall penetration depth with the stiffness coefficient k_e is applied to the teleoperater. The environment impedance given by the transfer function $Z_e = \frac{k_e}{s}$ yields a reflection factor (5) of

$$R(s) = \frac{k_e - bs}{k_e + bs}.$$

With this reflection coefficient the perceived impedance (4) is given by

$$Z_h(s) = b\frac{k_e + bs + (k_e - bs)e^{-sT}}{k_e + bs - (k_e - bs)e^{-sT}}.$$

The analytically derived approximation of the perceived impedance for low frequency is

$$Z_h(s) \approx \frac{k_h}{s}\left(1 + \frac{bT}{2k_e}s^2\right) \quad \text{for} \quad \omega < \frac{1}{3T}, \tag{9}$$

with

$$k_h = \frac{2bk_e}{2b + Tk_e}. \tag{10}$$

The lefthand factor is the low frequency component F_{lf} from (8). The right hand factor in (9) exhibits high pass behavior with a cut frequency of $\sqrt{2k_e/(bT)}$. The integrating characteristics of the low frequency component can be taken as good approximation of the low frequency behavior. As a result the perceived impedance in contact at low frequency has a springlike behavior but with a lower stiffness k_h than the environment stiffness k_e. A similar result for the perceived stiffness (10) is obtained in [12], there with the alternative approach of steady state consideration in the time domain.

The approach presented here can be applied to arbitrarily complex environment impedances. One of the main objective of this paper is to discuss the impact of the distortion of the perceived impedance on the perception of the environment from a human perception point of view as done in the following.

3.3 Transparency Facts

Psychophysical and objective interpretation of the transparency analysis results in the following facts:

Communication Induced Stiffness Reduction If the environment exhibits spring characteristics the operator perceives a substantially reduced stiffness. The environment feels softer as shown in Fig. 3. The reduction of the perceived stiffness becomes percentually higher for high environment stiffness. Higher values of the wave impedance b increase the transparency of stiff environments.

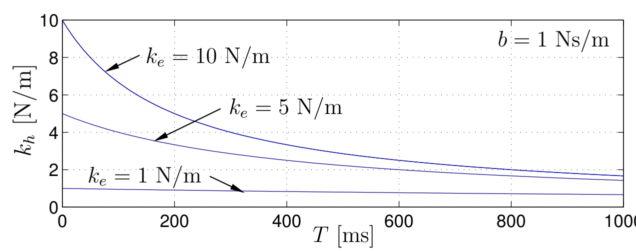

Figure 3: Perceived stiffness depending on delay for different environment stiffness coefficients.

Communication Induced Stiffness Bound The perceived stiffness can never exceed

$$k_{h,\text{max}} = \lim_{k_e \to \infty} k_h = \frac{2b}{T}\ , \tag{11}$$

only depending on the wave impedance b and the time delay T, *not* on the environment stiffness k_e. Fig. 4 shows the asymptotic behavior of the perceived stiffness for increasing environment stiffness. Considering the psychophysical fact that the human feels a wall to be rigid for $k_h \geq 24200$N/m [13] it becomes clear that only for very small time delays and very large wave impedances b a rigid wall can be realistically displayed with this control architecture.

Bounded Perceivable Environment Stiffness Change In some tasks not only the absolute value of the perceived stiffness is important but also the possibility to distinguish between differently stiff environments. This is especially im-

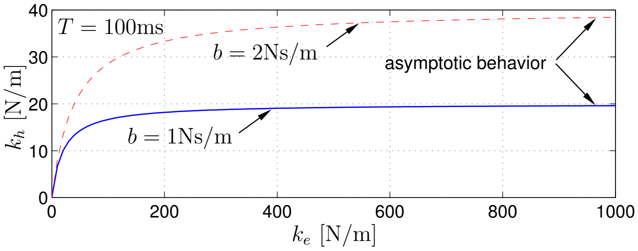

Figure 4: Perceived stiffness depending on environment stiffness.

portant for soft environments (e.g. in tele-surgery), where different characteristics have to be distinguished.

As indicated by the asymptotic behavior of the perceived stiffness in Fig. 4 at higher values of the environment stiffness any stiffness change in the environment results in a very small change in the perceived stiffness. If a change in the environment stiffness from k_e^0 to k_e should be perceivable than the corresponding percentual change in the perceived stiffness must be larger than the JND

$$\delta k_h = \frac{2b\delta k_e}{2b + T(1+\delta k_e)k_e^0} \geq JND$$

with $\delta k = |k - k^0|/k^0$ the percentual stiffness change, and $k_h^0 = k_h(k_e^0)$ according to (10). The change of perceived and environment stiffness is equal only for the marginal cases of zero delay or infinite wave impedance. At high delay and high environment stiffness a large change in the environment stiffness may result in a non-perceivable change of the perceived stiffness.

In fact, for a given delay and wave impedance there exists an upper bound in the environment stiffness $k_{e,\text{max}}$ at which a human is no longer able to detect the change to a very large (mathematically infinite) value of environment stiffness with $k_{e,\text{max}} = k_e([1 - JND]k_{h,\text{max}})$ (11). This maximum environment stiffness depending on the time delay is depicted in Fig. 5 for the two different JND assumptions reported in the literature (23% in [11], 8% in [10]).

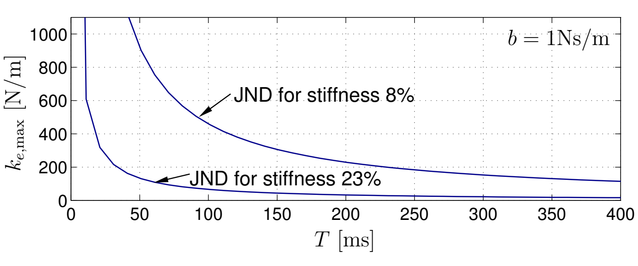

Figure 5: Maximum environment stiffness $k_{e,\text{max}}$ that allows the perception of the change to infinite environment stiffness.

In summary, using psychophysical insights for the transparency analysis give a first hint on the limits of the considered control architectures and thereby also on the possible application range from a human haptic perception point of view. In the following we will discuss a novel, psychophysically motivated control method to reduce the network traffic induced by the haptic feedback system.

4. Deadband Control

In [4] a deadband control approach for TPTA systems with time delay has been introduced. The system architecture extended by the deadband controller and the data reconstruction block, explained later, is depicted in Fig. 6. The deadband control is applied to the sampled wave variables $u_l(k)$ in the forward and $v_r(k)$ in the backward path; exemplarily the forward path is considered in the following.

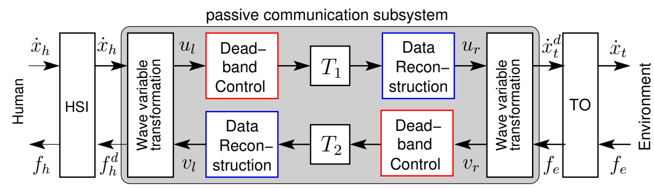

Figure 6: Deadband controlled haptic telepresence system.

The deadband controller in compares the previous value $u_l(k^*)$ sent over the network to the most recent value $u_l(k)$. If the absolute value of the difference between both values is within the deadband then no update is sent over the network. If the difference is outside the value $u_l(k)$ is transmitted and a new deadband is established around the value $u_l(k)$. The effect of the deadband control on the packet rate is visualized in Fig. 7. The relative deadband considered in [4] grows linearly by factor ϵ with the magnitude of the value $u_l(k^*)$. The absolute value Δ of the deadband is then given by

$$\Delta_{u_l}(k^*) = \epsilon|u_l(k^*)|. \tag{12}$$

If the signal $u_l(k^*)$ is close to the origin the deadband becomes infinitely small. Therefore the deadband is bounded from below $\Delta \geq \Delta_{\text{min}}$. If now the most recent transmitted value is close to the origin $|u_l(k^*)| < \Delta_{\text{min}}$ it may happen that the input to the deadband controller $u_l(k)$ changes the sign. For transparency the equality of the direction of motion or force at the HSI and the teleoperator is necessary, otherwise the teleoperator could move into the opposite direction of the HSI for example. Consequently, as soon as the input $u_l(k)$ changes the sign it must be transmitted. For a more formal description refer to [4]. The deadband control results in empty sampling instances at the receiver side, the missing values have to be reconstructed. The hold-last-sample (HLS) algorithm, commonly applied in NCS [7], potentially generates energy, hence cannot guarantee the passivity of the communication subsystem as shown in [14]. In [4] a passivity preserving data reconstruction algorithm, the energy supervised HLS/modified HLS, is introduced. Based on the

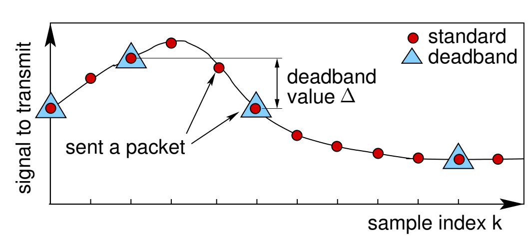

Figure 7: Effect of deadband control on packet rate.

observation of the energy balance either a strictly passive reconstruction algorithm, the modified HLS, or a less conservative, but potentially energy generating strategy, the HLS, is employed. The energy balance is computed from the transmitted energy. For more details refer to [4]. By passivity of the data reconstruction the passivity of the communication subsystem including the deadband algorithm at each sender, the channel, and the data reconstruction strategy at the corresponding receiver side is guaranteed. The deadband controlled haptic feedback system is stable.

The reconstructed wave variable values generally differ from the original value. As a result the decoded desired teleoperator velocity $\dot{x}_t^d$ may differ from the encoded HSI velocity $\dot{x}_h$, i.e. an unrecoverable position drift between the teleoperator and the HSI may occur. In order to achieve position transparency position-forward control, as proposed in [15], can be applied.

The human cannot detect arbitrarily small differences in velocity andd force signals, see e.g. [5,6]. This indicates that the human may not detect arbitrarily small differences in the wave variable signal (2) which is a combination of velocity and force signals. The following experiments validate that.

5. Psychophysical Experiments

Psychophysical experiments are conducted in order to determine the detection threshold for the relative deadband value ϵ. Furthermore, the effect of the deadband control on the packet rate is quantitatively evaluated.

5.1 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. 8. 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 communication subsystem are implemented. The control loops operate at a sampling rate of 1000 Hz representing the standard packet rate without deadband control. Position feedforward control is not applied here.

The communication subsystem consists of the communication line with constant delay of $T = 100\,\mathrm{ms}$, the wave variable transformation with the wave impedance set to $b = 250\,\mathrm{Ns/m}$, the deadband control, and the data reconstruction algorithms. The energy supervised HLS/modified HLS as proposed in [4] is applied. 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 heuristically set to a small value of $\Delta_{\text{min}} = 0.002\,\sqrt{\text{W}}$.

5.2 Procedure

Altogether 11 subjects (aged 22–30, 3 female, 8 male) were tested for their detection threshold of the deadband parameter ϵ. 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.

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 $\epsilon = 2\%$ and was increased after every incorrect answer up to maximal 30%. When an answer was correct, the same value was used again until 3 consecutive right answers were given. Then the value ϵ was decreased to the initial value 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.

5.3 Experimental Results

The specific results for every subject presented in Fig. 9 show that no one managed to feel the distortion introduced by a deadband value of 5% and only very few could discriminate 8% in a single trial. The lowest subject specific detection threshold, the average in over the three trials, $\epsilon = 8\%$

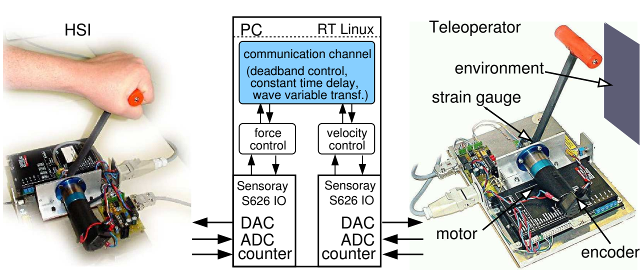

Figure 8: Experimental system architecture.

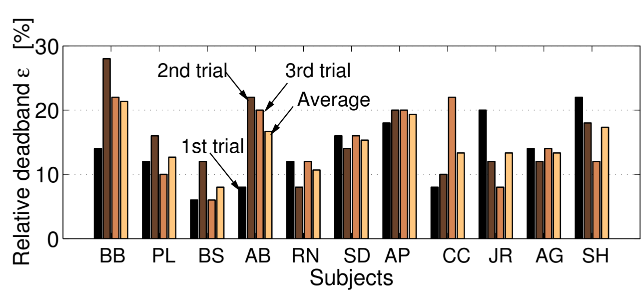

Figure 9: Overview of the subjects' results.

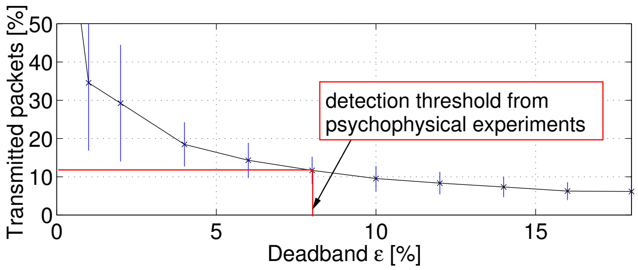

Figure 10: Influence of the deadband value on the number of transmitted packets.

is taken as appropriate deadband value. Interestingly, this result corresponds to the JND values for force (10%) and velocity (8%) perception.

The potential of the relative deadband control approach to reduce network traffic can be seen in Fig. 10, where the percentual average number of transmitted packet measured during the psychophysical experiments are depicted as a function of the deadband value; 100% corresponds to the standard packet rate, here 1000 Hz. The largest effect is observed at very low deadband values. With the determined detection threshold only 13% of the packets containing haptic information need to be transmitted without impairing transparency. As result we achieve an overall reduction of the network traffic in the haptic feedback system of 87%.

6. Conclusions

Human perception aspects are considered in this paper for the analysis and synthesis of haptic telepresence control architectures. Analysis methods for transparency of telepresence systems with wave variable transformation and time delay show that the perceived impedance is distorted from the environment impedance depending mainly on time delay. The transparency is evaluated using known detection thresholds in human haptic perception (JND) for mechanical parameters such as stiffness. According to the limited human perception of motion and force signals a relative deadband control approach to reduce communication network traffic is considered in this paper. The appropriate deadband is chosen in psychophysical experiments. A considerable network traffic reduction of up to 87% is achieved without degrading the human perceived transparency. Future studies will investigate the effect of different deadband definitions.

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