NETWORK TRAFFIC REDUCTION IN HAPTIC TELEPRESENCE SYSTEMS BY DEADBAND CONTROL

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Abstract: Current haptic (force feedback) telepresence systems operated over a communication network as, e.g. the Internet, require high packet rates for the transmission of the command and sensor signals. A novel approach to reduce the network traffic by means of deadband control is proposed. Data packets are only sent if the sampled signal changes more than a given threshold value. Passivity based reconstruction methods are introduced to reconstruct the untransmitted values at the receiver guaranteeing stability of the overall system. Experiments show that a packet rate reduction of up to 87% is achieved without impairing transparency.

Keywords: teleoperation, communication networks, deadband, delay

1. INTRODUCTION

A haptic (force feedback) telepresence (also called teleoperation) system combined with audio-visual communication support enables a human operator to be present and to actively perform complex manipulation tasks in possibly distant or differently scaled remote environments. Application areas reach from telemanufacturing and telemaintenance to telesurgery and rescue applications, see (Buss and Schmidt, 1999) for an overview.

In a haptic telepresence system the human operator manipulates the force feedback capable Human System Interface (HSI) thereby commanding the executing robot (teleoperator). While the teleoperator interacts with the usually unknown remote environment the haptic sensor data are fed back and displayed to the operator. If the operator feels directly connected to the remote environment then the system is called transparent. The sampled command signals and sensor data, both continuously generated realtime mediastreams, are transmitted over a packet switched communication network as, e.g., the Internet. Without further control measures time delayed data transmission destabilizes the haptic telepresence system resulting in a severe hazard to the safety of the human and the remote environment. In order to guarantee stability of haptic telepresence systems the passivity concept has sucessfully been applied (Anderson and Spong, 1989; Niemeyer and Slotine, 1991). The resulting control method (scattering or the equivalent wave variable transformation) stabilizes the system for arbitrarily large constant delay.

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As a result the wave variable signals are transmitted over the communication channel sampled at a rate equal to the sampling rate of the local control loops at the HSI and the teleoperator (500 – 1000 Hz). Commonly every set of sampled data is sent in individual packets leading to high packet transfer rates (500 –1000 packets per second). High packet rates are, however, hard to maintain over long distance packet switched networks. The induced network traffic and such the resource requirement (network cost) is unecessarily high.

In (Otanez *et al.*, 2002; Ishii and Basar, 2004) network traffic reduction in networked control systems (NCS) 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.

To the best knowledge of the authors for the first time deadband control is applied in haptic telepresence systems with time delay, which is assumed constant here. In this paper two approaches, namely constant and relative deadbands, are considered. Independently of the deadband definition, 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. According to (Hirche and Buss, 2004) the "hold last sample" (HLS) algorithm though is not passive; the stability of the telepresence system within the passivity framework cannot be guaranteed. Consequently, one of the key challenges is the development of a passive data reconstruction strategy. A modified HLS and a data reconstruction strategy with energy supervision is proposed. The performance is evaluated using telepresence transparency metrics in terms of the perceived stiffness by the operator and network performance metrics in terms of network traffic. The deadband approaches as well as the data reconstruction algorithms are compared in terms of performance, both in simulation and preliminary experiments.

The remainder of this paper is organized as follows. In Section 2 the background on haptic telepresence systems with time delay is reviewed. The deadband approach is introduced in Section 3, the proposed data reconstruction strategies are investigated in Section 4, followed by validating experiments in Section 5.

2. BACKGROUND

In haptic telepresence the human manipulates the HSI (variables indexed $_h$) applying the force f_h, see Fig. 1. Based on stability arguments the HSI velocity $\dot{x}_h$ is communicated to the teleoperator (index $_t$) 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 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.

Fig. 1. Haptic telepresence system architecture

2.1 The Passivity Approach

A common approach to analyze and synthesize telepresence system architectures with time delay is the passivity concept providing a sufficient condition for stability of the haptic telepresence 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 initial energy storage $E_{in}(0) = 0$, the energy balance

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

holds $\forall t > 0$, with P_{in} denoting the power input to the system, $\boldsymbol{u}$, $\boldsymbol{y}$ being the input and output vector. In classical telepresence architectures, as proposed in (Anderson and Spong, 1989), the appropriately locally controlled HSI and teleoperator exchange velocity and force signals as the mapping from velocity to force is generally passive, hence the subsystems human/HSI and teleoperator/environment are considered passive.

Considering time-delayed data transmission with the constant delay T in the forward and the backward path, the communication subsystem can be shown to be active. The scattering (or equivalently 'wave') transformation (Anderson and Spong, 1989; Niemeyer and Slotine, 1991) passifies the communication subsystem for *constant* delays with the transformation equations given by

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

with $b > 0$ a tunable parameter, also called characteristic impedance. The wave variables u_l (forward path) and v_r (backward path) are transmitted over the communication network and arrive at the corresponding receiver with the delay T

$$u_r(t) = u_l(t-T); \qquad v_l(t) = v_r(t-T). \qquad (3)$$

Note, that all the following considerations also apply for differents delay in the forward and backward path; only for ease of notation they are are assumed to be equal. The basic architecture is depicted in Fig. 2, the deadband control and data reconstruction blocks are discussed later. The power balance of the communication subsystem at any point in time is

$$P_{c,in} = \dot{x}_h \, f_h^d - \dot{x}_t^d \, f_e,$$

and expressed in wave variables using the transformation (2)

$$P_{c,in} = \frac{1}{2}(u_l^2 - u_r^2) + \frac{1}{2}(v_r^2 - v_l^2). \qquad (4)$$

The resulting energy balance of the communication subsystem for zero energy storage at $t = 0$, computed using (1) and (3), is non-negative

$$E_{c,in}(t) = \frac{1}{2} \int_{t-T}^{t} (u_l^2 + v_r^2) \, \mathrm{d}\tau \geq 0 \quad \forall t > 0.$$

The communication subsystem passive, in fact it is energetically lossless as the wave energy in u_l and v_r is only temporarily stored for the transit time T. According to (4) the energy balance can be considered separately for the forward and the backward path; passivity of the communication subsystem is guaranteed if

$$E_{cf,in}(t) = \int_{0}^{t} (u_l^2 - u_r^2) \, \mathrm{d}\tau \geq 0, \qquad (5)$$

holds for the forward path and equivalently with the right hand term in (4) for the backward path. Based on this fact the following considerations are done for the forward path only, but equally apply to the backward path.

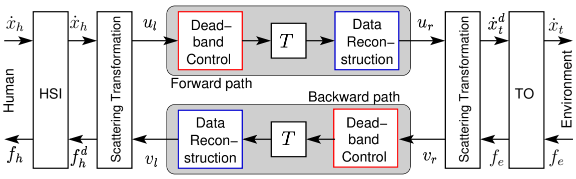

Fig. 2. Deadband controlled telepresence system

3. DEADBAND CONTROL

In order to reduce network traffic deadband control is proposed for the transmission of the sampled wave variable signals. The deadband controller, see Fig. 2, compares the most recently sent value $u_l(t')$ with the current value $u_l(t)$, $t > t'$. If the absolute value of the difference $|u_l(t') - u_l(t)|$ is smaller than the deadband width Δ then no update is sent over the network. Otherwise the value $u_l(t)$ is transmitted and a new deadband is established around the value $u_l(t)$. For further considerations an event indicator is defined

$$\Omega(t) = \begin{cases} 1 \text{ if } |u_l(t) - u_l(t')| \geq \Delta \\ 0 \text{ otherwise}, \end{cases}$$

indicating a 'packet sent' at time t if $\Omega(t) = 1$. For the ease of notation the following considerations are done in continuous time, the results equivalently hold for the discrete time case. The deadband can be defined to be of constant width or alternatively as a function of the input value $u(t')$. Both approaches are studied here.

3.1 Constant Deadband

The deadband value Δ is assumed to be of constant width. If the most recent transmitted value is close to the origin $|u_l(t')| < \Delta$ it may happen that the input to the deadband controller $u_l(t)$ changes the sign. The direction of the wave variable is considered to be the minimal information that must be transmitted for transparency. Hence, as soon as the input $u_l(t)$ changes the sign it must be transmitted. Therefore close to the origin the deadband is unequally spaced, while far from the origin the constant deadband value applies. In order to consider this exception the deadband is implicitely defined by

$$|u_l(t)| \in \begin{cases} [0, |u_l(t')| + \Delta) & \text{if } |u_l(t')| < \Delta \\ [|u_l(t')| \pm \Delta] & \text{if } |u_l(t')| \geq \Delta, \end{cases}$$

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

$$u_l(t) u_l(t') \geq 0, \qquad (6)$$

between transmitted values and current values at the sender is guaranteed.

3.2 Relative Deadband

The relative deadband grows linearly with the magnitude of the value $u_l(t')$. With the proportional factor ϵ the absolute value Δ of the deadband is defined by

$$\Delta_{u_l(t')} = \epsilon \cdot |u_l(t')|.$$

If the signal $u_l(t')$ is close to the origin the deadband becomes infinitely small. For practical application the deadband is lower bounded $\Delta \geq \Delta_{min}$. With the same sign consistency argument as for the constant deadband the relative deadband is implicitely defined by

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

such that (6) holds.

4. STABILITY

Independently of the deadband definition deadband control results in empty sampling instances at the receiver side. Hence, the missing data need to be estimated. In the following it is assumed that the most recent data u_r arrived at the time $t^* = t' + T$. With (3) the reconstruction operator can be denoted by

$$u_r(t) = \begin{cases} u_l(t-T) & \text{if } \Omega(t-T) = 1 \\ \zeta(u_r(t^*), t) & \text{otherwise,} \end{cases} \tag{7}$$

where $\zeta(\cdot)$ denotes the reconstruction algorithm. For stability the passivity of the communication subsystem with deadband control must be preserved. As only the data reconstruction algorithm but not the deadband controller itself effects the energy balance of the communication subsystem, see Fig. 2, for passivity, thus stability a passive data reconstruction algorithm is required. The known reconstruction algorithms like HLS are not passive in general (Hirche and Buss, 2004), a passive modification of the HLS algorithm is introduced in the following.

4.1 Modified HLS

Therefore the knowledge about the signal uncertainty at the sender is exploited: If no data packet arrives at the receiver at the time t, corresponding to $\Omega(t-T) = 0$, then the data value at the sender $u_l(t-T)$ and such the current value $u_r(t)$ at the receiver must lie within the deadband interval Δ of the most recently received value $u_r(t^*)$

$$|u_r(t^*)| - \Delta \leq |u_r(t)| \leq |u_r(t^*)| + \Delta,$$

where $t \geq t^*$ and Δ of constant or variable width. The modified HLS algorithm

$$\zeta(u_r(t^*), t) = u_r(t^*) - \text{sign}\{u_r(t^*)\} \cdot \Delta, \tag{8}$$

reconstructs the missing data at the lower (closer to the origin) end of the current deadband interval. Its passivity preserving character can be verified by considering the energy balance of the forward path (5). Computing the output wave power $u_r^2(t)$ with (7) and the reconstruction algorithm (8) yields

$$u_r^2(t) = \begin{cases} u_l^2(t-T) & \text{if } \Omega(t-T) = 1 \\ (|u_r(t^*)| - \Delta)^2 & \text{otherwise.} \end{cases}$$

As for constant delay (upper case) passivity is preserved only the time intervals where no data arrive (lower case) have to be considered. Considering the deadband definition at the sender side and the sign consistency definition (6) it is easy to show that for $t \geq t^*$ and $\Omega(t-T) = 0$

$$(|u_r(t^*)| - \Delta)^2 \leq u_l^2(t-T)$$

holds; the left hand term represents the lower bound of the input wave power.As a result the output wave power is always smaller or equal to the input wave power

$$u_r^2(t) \leq u_l^2(t-T) \quad \forall t > 0,$$

thereby fulfilling the passivity condition (5).

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 line clearly dissipates energy resulting in a decreased performance in general. As an alternative an energy supervised reconstruction strategy is considered.

4.2 Energy Supervised Data Reconstruction

Energy supervised data reconstruction is related to the time domain passivity concept (Hannaford and Ryu, 2002). An energy balance observer is introduced ensuring the passivity of the communication subsystem by choosing the appropriate reconstruction algorithm. Here two alternative strategies are considered: a non-conservative, but possibly energy generating standard strategy ζ_{np}, such as HLS, and a strictly passive strategy ζ_p, such as the modified HLS. The energy supervised data reconstruction algorithm is defined by

$$\zeta(t) = \begin{cases} \zeta_{np}(t) & \text{if } E_v(t) \geq 0 \\ \zeta_p(t) & \text{otherwise.} \end{cases} \tag{9}$$

with

$$E_v(t) = \int_0^{t'} u_l^2 \, \mathrm{d}\tau - \int_0^t u_r^2 \, \mathrm{d}\tau, \tag{10}$$

being the energy balance computed at the receiver side, see Fig. 3. The difference to the energy balance (5) results from the fact that the input wave energy is assumed to be transmitted in the same data packet as the wave variable. Hence an update is available only until the time t' when the most recent packet was sent. The energy supervised data reconstruction algorithm given by (9), (10) is passive. The lower case in (9) by definition results in a non-negative energy balance, hence for passivity considerations only the upper case has to be investigated. With the condition $E_v(t) \geq 0$ the passivity condition (5) expressed with (10)

$$E_{cf,in}(t) = E_v(t) + \int_{t'}^{t} u_l^2 \, \mathrm{d}\tau \geq 0$$

is always satisfied, as both terms are non-negative, hence the overall algorithm is passive.

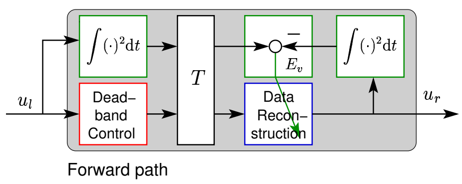

Fig. 3. Energy supervised data reconstruction.

The observed energy balance E_v can also be interpreted as the storage function of some virtual energy storage element. The energy stored therein represents the excess passivity of the communication line that may compensate the temporal shortage of passivity of some less conservative reconstruction algorithm. For further investigations the modified HLS (8) is taken as passive reconstruction strategy ζ_p and the standard HLS

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

as non-passive strategy in (9).

4.3 Simulations

For the following simulations the constant delay of $T = 100$ms, and the deadband control with equal parameters in the forward and the backward path are assumed. The deadband control including the data reconstruction distorts the signal as shown in Fig. 4(a) and (b) where the outgoing signal $u_r(t)$ without deadband control is compared to the output with constant and relative deadband combined either with the modified HLS (8) or the energy supervised reconstruction algorithm (9). For the energy supervised reconstruction the switching to the modified HLS can be observed. The passivity of the communication subsystem for all considered deadband/reconstruction approaches is indicated by the positive values of the energy balance of the forward path in Fig. 4(c).

In a further simulation the performance of the reconstruction strategies is evaluated in terms of the perceived stiffness and the percentage of transmitted packets. Therefore the HSI is modeled as a velocity source providing a constant velocity of $\dot{x}_h(t) = 1$m/s. The teleoperator with a mass of $m_t = 0.23$kg and a damping coefficient of $b_t = 0.04$kg/s is velocity controlled with

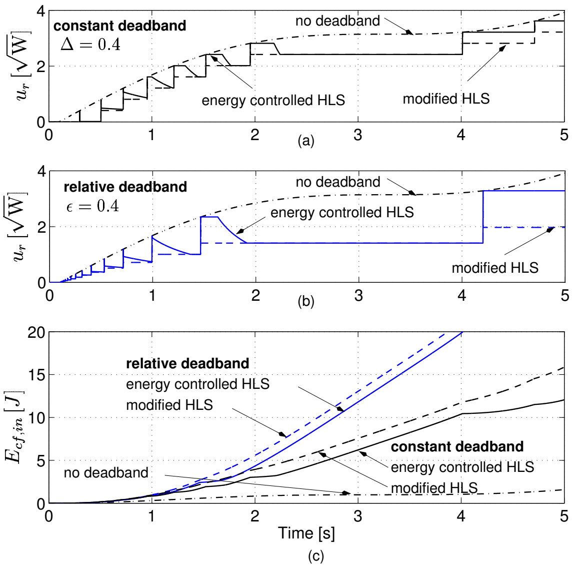

Fig. 4. Output signal with constant (a), relative (b) deadband and energy balance of the communication forward path (c)

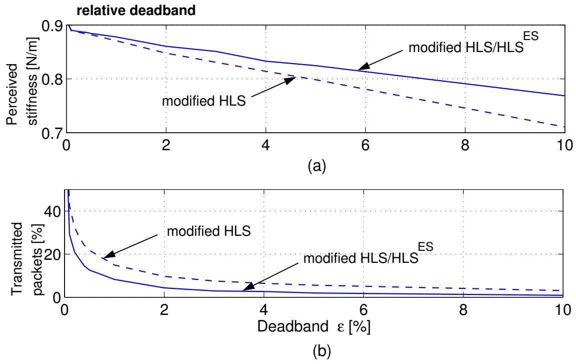

Fig. 5. Perceived stiffness (a) and number of transmitted packets (b) depending on relative deadband value ϵ

a proportional $P = 100$Ns/m and an integral gain $I = 10$N/m. The environment has a stiffness coefficient $k_e = 1$N/m. The characteristic impedance is set to $b = 1$Ns/m. The coefficient of the perceived stiffness, determined by a least square identification from the velocity/force signals, is depicted depending on the value of the relative deadband in Fig. 5(a), the percentage of the transmitted packets is shown in Fig. 5(b).

Generally, with increasing deadband the environment feels softer. With the energy supervised algorithm the environment feels stiffer than with the modified HLS, furthermore less packets are transmitted, hence the energy supervised algorithm outperforms the modified HLS as reconstruction strategy.

5. EXPERIMENTS

The goal of the experiment is to rate the deadband/reconstruction strategies with respect to the telepresence transparency and network performance. Therefore the combinations of constant and relative deadband approaches with the modified HLS and the energy supervised data reconstruction are compared.

The experimental setup consists of two identical 1-DOF haptic displays connected to a PC and a still wall 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 communication subsystem with deadband control, data reconstruction, time delay, and scattering transformation are implemented. 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 heuristically

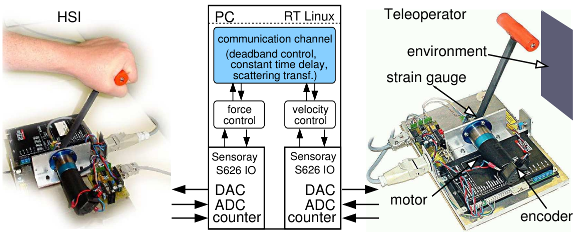

Fig. 6. Experimental setup

set to a small value of $\Delta_{min} = 0.002\sqrt{\mathrm{W}}$. The delay, equal in the forward and the backward path, is constant $T = 100\mathrm{ms}$, the characteristic impedance is set to $b = 125\mathrm{Ns/m}$.

During the experiment the deadband value is varied with $\Delta \in \{0.002, 0.02, 0.1, 0.2, 0.4\}\sqrt{\mathrm{W}}$ and $\epsilon \in \{0.1, 1, 5, 10, 20\}\%$. The stiffness parameter k_h perceived by the operator during touching the wall is computed by means of a least square identification on the position and force signals measured at the HSI. For comparison the perceived stiffness without deadband control is used which is $k_{h,0} = 540\mathrm{N/m}$. The normed stiffness error $\frac{k_{h,0}-k_h}{k_{h,0}}$ depending on the percentage of transmitted packets without deadband control is depicted in Fig. 7.

Highest performance in this experiment shows the constant deadband approach with energy supervised data reconstruction. In order to display the same stiffness fewer packets need to be transmitted than in all other approaches. At a deadband value of $\Delta = 0.02\sqrt{\mathrm{W}}$ only 13% of the original number of packets are transmitted. The corresponding stiffness error is 5% , that according to psychophysical studies is not perceivable by the human (Burdea, 1996). Consequently, a packet rate reduction of 87% is achieved without degrading transparency which corresponds to the results from (Hirche *et al.*, 2005) where the deadband approach without communication delay is studied

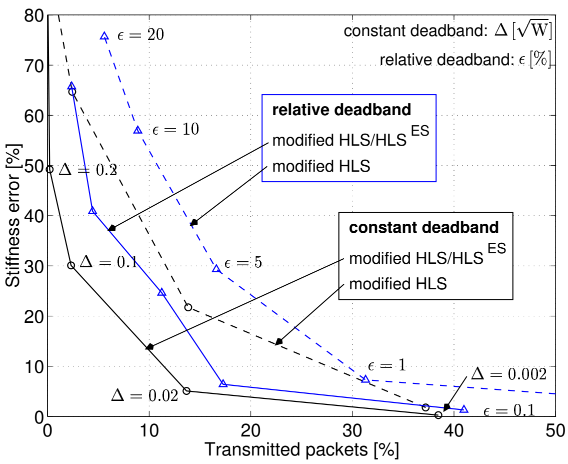

Fig. 7. Normed error of perceived stiffness depending on the percentage of transmitted packets

6. CONCLUSION

An innovative approach to reduce the network traffic in haptic telepresence systems with time delay is successfully applied in this paper. Therefore a constant and a relative deadband approach are investigated. Stability is achieved by passive data reconstruction. Without impairing transparency a major packet rate reduction of up to 87% is achieved, validated by experiments. Future work includes the evaluation of the transparency optimal deadband parameters by psychophysical experiments and the extension to communication channels with time-varying delay and packet loss.

ACKNOWLEDGEMENT

This work was partly supported by the DFG Collaborative Research Center SFB453.

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