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. We propose a novel approach to reduce the network traffic by means of deadband control. Data packets are only sent if the sampled signal changes more than a given threshold value. Passivity based estimation methods are introduced to reconstruct the missing values for the resulting empty sampling instances at the receiver. Thereby the passivity/stability of the overall system is achieved. Experiments are conducted in order to show the validity of our approach.

Keywords: teleoperation, communication networks, delay, deadband

1. INTRODUCTION

A haptic (force feedback) telepresence system together with common state-of-the-art multimedia (visual and auditory feedback) 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.

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 teleoperation systems the passivity concept has sucessfully been applied (Anderson and Spong, 1989). The resulting control method (scattering transformation) stabilizes the system for arbitrary constant delay.

As a result of the scattering transformation the sampled wave variable signals are transmitted over the communication channel. Naturally the sampling rate of the wave variable signals is equal to the sampling rate of the local control loops at the HSI and the teleoperator being in the range of 500 – 1000 Hz. Commonly every set of sampled data is sent in individual packets in order to keep the packetization delay as small as possible. High packet rates (500 to 1000 packets per second) are hard to maintain over long distance packet switched networks. Additionally the probability of congestion is increased leading to higher transmission delay and packet loss.

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

As far as known to the authors for the first time the deadband control approach is investigated for application in haptic telepresence systems with time delay. The first of two key challenges is the proper definition of the deadband without impairing the transparency of the haptic telepresence system, the second is the definition of the data reconstruction strategy at the receiver without violating the passivity requirement.

For the deadband definition in this paper two approaches, namely constant and relative deadbands, are compared with respect to their performance. The performance is evaluated using a network performance metrics in terms of network traffic and a telepresence transparency metrics in terms of the perceived stiffness by the operator. The second key challenge is the data reconstruction at the receiver side as deadband control results in empty sampling instances. In (Otanez *et al.*, 2002) the values of the missing data are estimated by holding the value of the last received sample. The "hold last sample" (HLS) algorithm is non-passive as shown in (Hirche and Buss, 2004); as a result the stability of the telepresence system cannot be guaranteed. Exploiting the knowledge of the deadband a modified HLS algorithm is proposed here reconstructing the data such that passivity cannot be sacrificed. As this turns out to be a very conservative reconstruction algorithm furthermore the augmentation of the system with a virtual energy storage is proposed. As a result less conservative reconstruction algorithms can be applied without sacrificing the passivity/ stability of the overall system. Both reconstruction algorithms are compared in terms of performance, both in simulations and experiments.

The remainder of this paper is organized as follows. In Section 2 the background on haptic telepresence with time delay is studied. The deadband definition together with the data reconstruction strategies followed by simulation is given in Section 3. Experiments are presented in Section 4. Section 5 concludes this paper with a brief discussion and an outline of future work.

2. BACKGROUND

2.1 System Architecture

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 (inedx $_t$) 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.

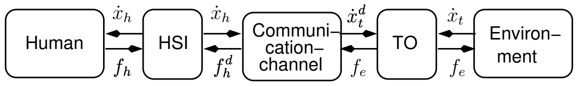

Fig. 1. Teleoperation system architecture

2.2 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 energy storage at $t = 0$, 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. 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 transformation (Anderson and Spong, 1989) passifies the communication subsystem for *constant* delays with the transformation equations given by

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

The wave variables u_l (forward path) and v_r (backward path) are sent to the communication subsystem and arrive at the corresponding receiver with the delay T

$$u_r(t) = u_l(t - T) \qquad v_l(t) = v_r(t - T). \tag{3}$$

The basic architecture is depicted in Fig. 2, the deadband control and data reconstruction blocks are discussed later. The power input into the communication subsystem at any point in time is

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

Substituting with the transformation from (2)

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

and integrating using (3) we find that all input power is stored in the communication subsystem according to

$$E_{c,in}(t) = \int_0^t P_{in}\,\mathrm{d}\tau = \frac{1}{2}\int_{t-T}^t (u_l^2 + v_r^2)\,\mathrm{d}\tau \geq 0$$

assuming zero energy storage at $t = 0$. The wave energy in u_l an v_r is temporarily stored for the transit time T, rendering the communication subsystem not only passive but lossless.

Note that according to (4) the energy balance can be seperatly considered for the forward and the backward path. Passivity of the communication subsystem is guaranteed if

$$E_{cf,in}(t) = \int_0^t (u_l^2 - u_r^2)\,\mathrm{d}\tau \geq 0, \tag{5}$$

and

$$E_{cb,in}(t) = \int_0^t (v_r^2 - v_l^2)\,\mathrm{d}\tau \geq 0,$$

which for pure delay holds. Using this symmetry in the following considerations are done for the forward path only, but equally apply for the backward path.

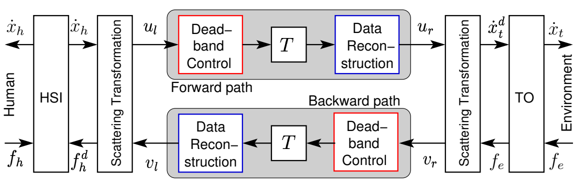

Fig. 2. Deadband controlled teleoperation system

3. DEADBAND CONTROL

3.1 Definition

In order to reduce network traffic deadband control is proposed for the transmission of the sampled wave variable signals. The deadband controller compares the previous value $u_l(t')$ sent over the network to the most recent value $u_l(t)$. If the absolute value of the difference $|u_l(t') - u_l(t)|$ is within the deadband Δ then no update is sent over the network. If the difference is outside the value $u_l(t)$ is transmitted and a new deadband is established around the value $u_l(t)$. The deadband control operator is defined by

$$\Omega(t) = \begin{cases} 1 \text{ if } |u_l(t) - u_l(t')| < \Delta \\ 0 \text{ otherwise.} \end{cases} \tag{6}$$

If $\Omega(t) = 1$ the deadband is active and no data is sent. The deadband Δ can be defined as constant value or alternatively as a function of the input value $u(t')$. Both approaches are investigated here.

3.2 Constant Deadband

A constant deadband value Δ is defined. 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 an information that must be transmitted. Hence, as soon as the input $u_l(t)$ changes the sign it must be transmitted. Therefore it is necessary to weaken the lower bound Δ. Close to the origin the deadband is unequally spaced, far from the origin the constant deadband value Δ applies. The deadband is implicitely defined by

$$|u_l(t)| \in \begin{cases} [0, |u_l(t')| + \Delta) & \text{if } |u_l(t')| < \Delta \\ [|u_l(t')| \pm \Delta] & \text{if } |u_l(t')| \geq \Delta. \end{cases} \tag{7}$$

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

$$u_l(t) u_l(t') \geq 0. \tag{8}$$

3.3 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

$$\Delta_{u_l(t')} = \epsilon \cdot |u_l(t')|. \tag{9}$$

If the signal $u_l(t')$ is close to the origin the deadband becomes infinitely small. For practical application the deadband is bounded from below $\Delta \geq \Delta_{min}$. With the same sign consistency (8) argumentation as for the constant deadband the relative deadband is implicitely defined by

$$|u_l(t)| \in \begin{cases} [0, |u_l(t')| + \Delta_{min}) & \text{if } |u_l(t')| < \Delta_{min} \\ [|u_l(t')| \pm \Delta_{u_l(t')}] & \text{if } |u_l(t')| \geq \Delta_{min}, \end{cases} \tag{10}$$

such that (8) holds.

In the following it is assumed that the deadband denoted by Δ fulfills (7) for the constant deadband, (9) and (10) for the relative deadband.

3.4 Passive Data Reconstruction

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

$$u_r(t) = \begin{cases} \zeta(u_r(t^*), t) & \text{if } \Omega(t-T) = 1 \\ u_l(t-T) & \text{otherwise,} \end{cases} \tag{11}$$

where $\zeta(\cdot)$ denotes the reconstruction algorithm.

Exploiting the knowledge that during active deadband control $\Omega(t-T) = 1$ the current data value at the sender $u_l(t-T)$ with $t \geq t^*$ must lie within the deadband interval of the last received value

$$|u_r(t^*)| - \Delta \leq |u_r(t)| \leq |u_r(t^*)| + \Delta, \tag{12}$$

where Δ stands for the deadband around $u_r(t^*)$, which can be defined as constant or relative deadband. The missing data can be estimated at the lower end of the interval

$$\zeta_p(u_r(t^*), t) = u_r(t^*) - \text{sign}\{u_r(t^*)\} \cdot \Delta \tag{13}$$

This modified HLS algorithm results in a strictly passive communication line. This can be verified considering the energy balance of the forward path (5). Computing the output wave power $u_r^2(t)$ with (11) and the reconstruction algorithm (13) yields

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

Considering the deadband definition at the sender side and the sign consistency definition (8) it is easy to show that

$$(|u_r(t^*)| - \Delta)^2 \leq u_l^2(t-T) \quad \text{if } \Omega(t-T) = 1$$

for $t \geq t^*$ as this represents the estimation of the minimum input wave power during active deadband control. As a result the output wave power is always smaller or equal to the input wave power of the forward path

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

thereby fulfilling the passivity condition (5). With this data reconstruction algorithm the communication line clearly dissipates energy. The dissipative character results in a decreased performance of the haptic telepresence system.

In order to increase the performance it is proposed to augment the communication line at the receiver side with a virtual energy storage element storing the wave energy that would be dissipated otherwise. The storage requires the knowledge of the input wave energy, that has to be transmitted together with the wave variable as proposed in (Niemeyer and Slotine, 1998). As a result the input energy only at the time of non-active deadband control t' is known at the receiver. As the input energy is a monotonically increasing function the value of the input energy at time t' can be interpreted as a conservative estimation of the input energy for $t > t'$. In order to guarantee passivity the energy of the virtual energy storage element with zero initial energy must be positive semidefinite

$$E_v(t) = \int_0^{t'} u_l^2 \, d\tau - \int_0^{t} u_r^2 \, d\tau \geq 0, \tag{14}$$

with $t \geq t'$. With this requirement the passivity condition (5) expressed as

$$E_{cf,in}(t) = E_v(t) + \int_{t'}^{t} u_l^2 \, d\tau \geq 0, \tag{15}$$

is always satisfied, as both terms are positive semidefinite. In order to bound the energy output for practical application the virtual energy storage is saturated $E_v(t) \leq E_{max}$. The energy stored can be interpreted as the excess passivity of the communication line that may compensate the temporal shortage of passivity of some less conservative reconstruction algorithm as e.g. a simple HLS (Hirche and Buss, 2004). If the storage element reaches its initially stored energy value, than a strictly passive reconstruction strategy like the proposed modified HLS (13) is applied again.

Assuming a simple HLS as alternative data reconstruction algorithm

$$\zeta_{np}(u_r(t^*), t) = u_r(t^*) \tag{16}$$

the complete energy controlled reconstruction algorithm is defined by

$$\zeta(t) = \begin{cases} \zeta_{np}(t) & \text{if } E_{max} < E_v(t) \\ \zeta_p(t) + k\dfrac{E_v(t)}{E_{max}}\Delta & \text{if } 0 \leq E_v(t) \leq E_{max} \\ \zeta_p(t) & \text{otherwise.} \end{cases} \tag{17}$$

The middle case results a smoother transition between the reconstruction algorithms ζ_{np} and ζ_p with k as a tuning parameter determining slow or fast transition to the passive reconstruction algorithm ζ_p. With this data reconstruction algorithm the virtual energy is always positive semidefinite thereby fulfilling (14). There is never more energy extracted from the communication line than the energy input until t'. As a result the energy balance of the communication line (15) is always larger than zero, hence the data reconstruction is passive. With respect to the lack in space the proof is omitted here.

3.5 Simulations

The effect of the deadband control together with the reconstruction algorithms is investigated in simulations with a constant delay of $T = 100$ms in the forward and the backward path. The deadband control including the data reconstruction distorts the signal as shown in Fig. 3(a) and (b), where the outgoing signal $u_r(t)$ without deadband control is compared to the output with constant and relative deadband. The deviation for the relative deadband increases with the value of $u_r(t*)$. Furthermore the modified HLS (13) as data reconstruction strategy is compared with the energy controlled HLS (17) with the tuning parameter set to $k = 1$. Note that in the starting phase the energy level of the virtual storage element is not high enough to allow a simple HLS until the next packet arrives, after a while it transits to the modified HLS again. Generally higher deviation from the original signal results in a more conservative behavior corresponding to higher positive values in the energy balance of the communication line in Fig. 3(c). Clearly, the modified HLS is conservative compared to the energy controlled HLS.

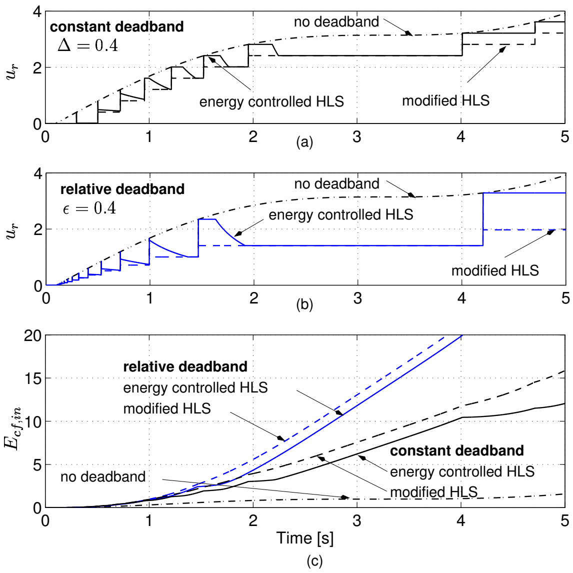

Fig. 3. Output signal with constant (a), relative (b) deadband and energy balance of the communication forward path (c)

The effect of the choosen deadband/reconstruction approach on the perceived stiffness as performance metrics for the telepresence system and the packet number as performance metrics for the communication network is investigated in further simulations.

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 the proportional gain of $P = 100$ and an integral gain of $I = 10$. The environment has a stiffness coefficient of $k_e = 1$N/m. The scattering parameter is set to $b = 1$. The deadband control applies with the same deadband parameter and reconstruction algorithm in the forward and the backward path. The simulation time is 10s.

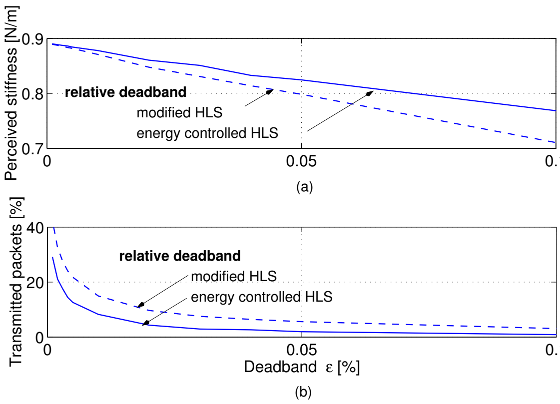

Fig. 4. Perceived stiffness (a) and number of transmitted packets (b) depending on relative deadband value ϵ

In Fig. 6(a) the coefficient of the perceived stiffness is depicted depending on the value of the deadband. With increasing deadband the environment feels softer. Applying the energy controlled HLS as data reconstruction strategy for the same deadband value the environment feels stiffer than with the modified HLS. This corresponds to the formerly found conservative character of the latter strategy. Interestingly, applying the same deadband value the packet rate with energy controlled HLS is the lower than for the modified HLS, hence the data reconstruction algorithm influences the packet rate. Generally the energy controlled HLS outperforms the modified HLS as reconstruction strategy, this approach shows the highest performance in terms of network and telepresence system performance. A general rating on the choice of deadband algorithm though is not obvious from the performed simulations. Experiments are conducted in order to evaluate these approaches from a practical point of view.

4. EXPERIMENTS

4.1 Experimental Setup

In the experiments the constant and the relative deadband approach with modified (13) and energy controlled HLS (17), hence four cases are compared. Again the perceived stiffness in terms of a stiffness error and the number of transmitted packets are choosen as evaluation criteria.

The experimental setup consists of two identical 1-DOF haptic displays connected to a PC and a stiff wall as the environment, see Fig. 5. 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

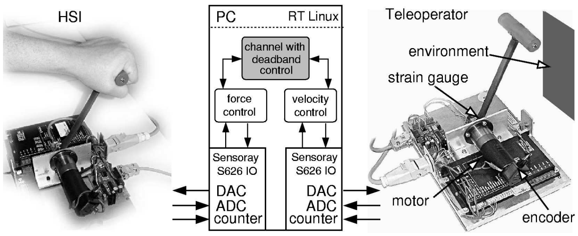

Fig. 5. Experimental setup

algorithms are implemented. The control loops operate at a sampling rate of $T_A = 1\text{ms}$.

The deadband control approach and the data reconstruction strategy are equally applied in the forward and the backward path with the same deadband value. The minimal deadband for the relative deadband approach is set heuristically to a small value of $\Delta_{min} = 0.001$. The delay in the forward and the backward path is constant $T = 100\text{ms}$.

During the experiment the deadband value is varied with $\Delta, \epsilon \in \{0.001, 0.01, 0.05, 0.1, 0.2\}$. 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 at the HSI. For comparison the perceived stiffness without deadband control is used which is $k_{h,0} = 22\text{N/m}$. The normed stiffness error $\frac{k_{h,0}-k_h}{k_{h,0}}$ is depicted depending on the the number of transmitted packets in Fig. 6. The number of packets is given as the percentage of transmitted packets number without deadband control. If the network traffic is evaluated by volume the additional transmission of the input energy together with the wave variables for the energy controlled HLS as date reconstruction has to be considered. As the additional amount of data (4 byte) in each packet is comparably low to the protocol overhead of UDP (20 byte) the effect

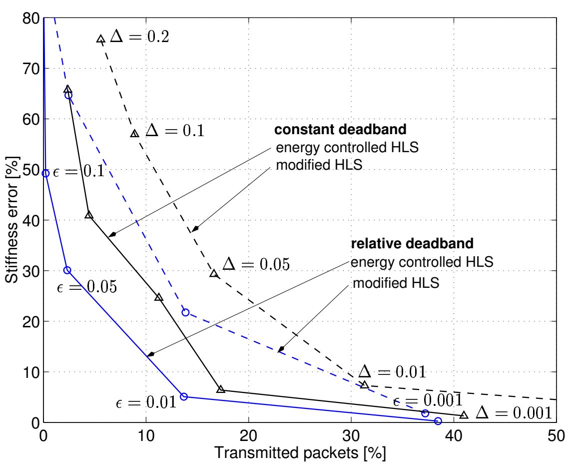

Fig. 6. Stiffness error depending on the number of transmitted packets

is assumed to be negligible. Thus the number of packets is valid as measure for network traffic.

Highest performance in contact situation shows the relative deadband approach with energy controlled HLS. In order to display the same stiffness fewer packets need to be transmitted than for all other approaches. At a deadband value of $\epsilon = 0.01$ only 15% of the original number of packets are transmitted in this experiment. The stiffness error for the energy controlled HLS is only 5% , that according to psychophysical studies is not perceivable by the human (Burdea, 1996). With the same deadband value for the modified HLS the stiffness error of 22% is substantially higher validating the simulation results. Similar results are obtained for free space motion with the position error between HSI and teleoperator as performance measure. Due to the lack of space these results are not shown here.

5. CONCLUSION

An innovative approach to reduce the packet rate and thereby the network traffic in haptic telepresence systems with time delay is presented in this paper. Based on a deadband control approach two different strategies are investigated, namely a constant and an relative deadband approach. A passive data reconstruction algorithm is proposed. The effectiveness of the network traffic reduction strategies is validated and compared in experiments.

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