A NOVEL, PSYCHOPHYSICALLY MOTIVATED TRANSMISSION APPROACH FOR HAPTIC DATA STREAMS IN TELEPRESENCE AND TELEACTION SYSTEMS

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ABSTRACT

One of the key challenges in telepresence and teleaction systems is the fact that a global control loop is closed over a communication network. The transmission delay of haptic information is extremely critical. Therefore, new data samples from the haptic sensors are typically immediately forwarded to the receiver which leads to a large number of packets being generated when using the Internet as the communication infrastructure. We present a novel approach to reduce the amount of packets and therefore data communicated in a telepresence and teleaction system. Our method uses a passive deadband transmission approach which only delivers data packets over the network when the sampled sensor data changes more than a given threshold value. The threshold value is determined by psychophysical experiments. This approach leads to a considerable reduction (up to 90%) of packet rate and data rate without sacrificing fidelity and immersiveness of the system.

1. INTRODUCTION

In a telepresence and teleaction (TPTA) system a teleoperator (TOP), typically a robot equipped with different kinds of sensors and actors, is controlled by an operator (OP), a human being connected to a human system interface (HSI). The HSI reflects the sensor data acquired by the robot in a remote environment to the OP using displays for visual, auditory and haptic data. While video and audio data is transmitted only in one direction (to the OP), haptic data (position/velocity and force) has to be communicated in both directions. The OP commands the desired TOP position/velocity through the HSI. The contact force at the TOP is communicated back to the OP side and so, a global control loop is closed over the communication system. Because transmission delay destabilizes the overall system resulting in a severe hazard for the OP and the environment, the system has to be stabilized by means of sophisticated control measures, for an overview see e.g. [1].

In real life the communication system can be a wired or wireless network with or without packet switched data transfer. Because of its high availability the Internet is a very interesting candidate for the transmission of this multimodal data. Unfortunately, the Internet as a communication channel for high rate real-time data is far from being optimal. Varying time delays mostly due to congestions in routers appear as well as packet loss.

Current TPTA systems like [2] require fast update rates (500–1000 Hz) for the local control loops for good tracking performance. To keep the packetization delay as small as possible, every set of sampled sensor data has to be sent in individual packets leading to small packet payloads between 10 and 50 bytes, depending on the number of degrees of freedom (DOF) and the sample resolution. Hence a large protocol overhead in each packet is observed. An UDP/IP packet without network headers and additional application headers is already 24 bytes large (20 byte IP, 4 byte UDP). So although the payload of haptic data is not very large, the resulting bit rate on the network is considerably larger (50% to 100%) than this. This behavior combined with the fact that high packet rates (500 to 1000 packets per second) are always hard to maintain over long distance packet switched networks leads to the conclusion that a technique for packet rate reduction would be of great benefit in order to allow TPTA applications over the Internet.

In this paper a novel approach for packet rate reduction in TPTA systems is proposed exploiting human haptic perception. It is based on deadband transmission, a method that has recently been employed in networked control systems, see [3]. For the first time the deadband transmission approach is applied to TPTA systems. This preliminary study investigates the potential of the approach by means of psychophysical evaluation under the assumption that the communication channel has no delay and no packet loss.

The remainder of this paper is organized as follows. In Section 2 we present our deadband transmission approach followed by a stability consideration in Section 3. We describe the psychophysical experiment that is used to evaluate the appropriate transmission parameters in Section 4 along with its results in Section 5. Section 6 concludes this paper with a brief discussion and an outline of future work.

2. DEADBAND TRANSMISSION

The main idea of our deadband transmission approach is based on the fact that packets carrying haptic information in a telepresence and teleaction system need to be transmitted only in case of changing sensor data sample values. This change could be either due to movement of the OP or because of force variation at the TOP. In case nothing in the system changes, no data has to be transmitted.

If for example the TOP has no contact with the surrounding environment its force sensor samples will be almost zero (some

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noise will always be detected but shall be neglected here). Therefore it is not necessary to transmit any packets containing force values over the network. Once contact forces are measured and exceed a certain threshold value ϵ, a packet containing the latest force measurement f is sent. Around this value f a new threshold interval $[f-\epsilon, f+\epsilon]$ is established and only if a consecutive force sample lies outside this interval, a new packet is sent. During the time interval where no new packet arrives the set value of the local control loop at the receiver is generated by a modified "hold last sample" algorithm (see Section 3). As a result the deadband control decreases the bit rate and thereby the network load.

This algorithm can be used for different types of sensor data. The most important types, position, velocity, and force are briefly discussed in the following, as they allow for individual optimizations because of their different nature.

2.1. Position values

In case of position tracking the proposed algorithm works well as long as the threshold value ϵ is small enough to be able to track the smallest possible motion. This has to be near the resolution of the display device in most cases and therefore the algorithm may not be as efficient with this type of sensor data as with the following two. Still, if ϵ is set above the noise level of the sensors, data will be only transmitted in case of motion.

2.2. Velocity values

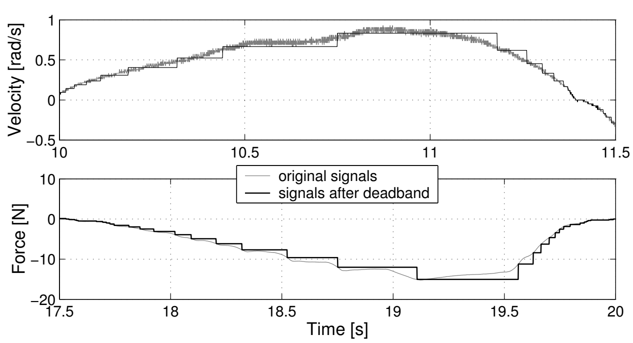

Fig. 1. Velocity and force signals before and after applying the proposed deadband transmission algorithm with $p = 0.25$

Based on the fact that a human being is only able to discriminate velocity changes which have a magnitude proportional to the velocity itself [4] (JND: Just Noticeable Difference) a linearly growing threshold interval can be used. For example a change in velocity from standstill to very slow motion by a certain Δv can be discriminated very well. If a faster motion changes by the same Δv this change is very unlikely to be detected. So, in this case we are not using a constant ϵ as our threshold value but use an $\epsilon(v)$ instead:

$$\epsilon(v) = p \cdot v \tag{1}$$

p is the percentage of change in velocity which is just not noticable. This p is determined in psychophysical experiments in Section 4. The effect of the deadband algorithm for velocity is shown in the upper part of Figure 1; the data have been recorded during a test session of a psychophysical experiment. Note the increasing size of the deadband with increasing velocity.

2.3. Force values

Similar to Section 2.2 there is also a detection threshold (JND) for force changes which is proportional to the force itself. According to numerous psychophysical studies mentioned in [5, 6], the JND for force perception with hand and arm is around 10%. We will present later on that this is also a good measure for p in the force dependant threshold value:

$$\epsilon(f) = p \cdot f \tag{2}$$

In the lower part of Figure 1 a force plot using our deadband transmission algorithm is shown. The deadband size increases with force magnitude according to the JND for force perception.

3. STABILITY OF CONTROL

In a TPTA system a global control loop is closed over the communication network. Even small delays destabilize the system resulting in severe hazard for the OP, TOP and objects in the environment. The stability of TPTA systems is commonly analyzed by means of a passivity approach. A passive system does not generate energy. A system composed of passive subsystems is passive itself and thereby stable. In classical TPTA architectures as proposed in [7] the appropriately locally controlled HSI and TOP exchange velocity v and force f signals as shown in Figure 2. The mapping from velocity to force is generally passive, hence the TOP/environment and the HSI/OP are assumed to be passive subsystems. Additional position feedforward to the TOP with a saturated control output is possible without sacrificing passivity [8].

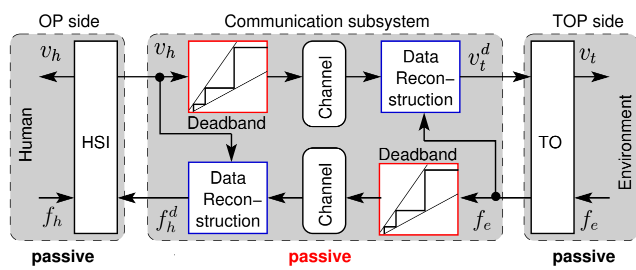

Fig. 2. Telepresence and teleaction system control architecture with deadband control and passive data reconstruction

In order to guarantee the passivity/stability of the overall system the bilateral communication subsystem including the deadband algorithm at each sender, the channel, and the data reconstruction strategy at the corresponding receiver side must be passive. In this paper the channel is assumed to have no delay and no packet loss. The deadband control results in empty sampling instances at the receiver side where the local control loops work at a fixed sampling rate. If missing data values — TOP velocity v_t^d and HSI force f_h^d — are reconstructed by a simple "hold last sample" the communication subsystem is not passive in general, see [9]. Assuming that for the time Δt no newer packet has arrived due to the deadband control we propose a modified "hold last sample" according to

$$v_t^d(t) = v_t^d(t-\Delta t) - \text{sign}\{f_e(t)\} \cdot \epsilon(v)$$
$$f_h^d(t) = f_h^d(t-\Delta t) + \text{sign}\{v_h(t)\} \cdot \epsilon(f),$$

where $v_t^d(t-\Delta t)$ and $f_h^d(t-\Delta t)$ represent the value of the last arrived packet. This algorithm reconstructs the data value either at the lower or the upper bound of the deadband such that passivity is preserved. For a sketch of a proof the energy balance of the bilateral communication line is considered which for passivity must fulfill

$$\int_0^t (v_h f_h^d - v_t^d f_e)\, \mathrm{d}\tau \geq 0 \quad \forall t > 0 \tag{3}$$

for all admissible inputs v_h and f_e. Without the deadband control equality holds as $v_t^d = v_h$ and $f_h^d = f_e$; the subsystem is passive (lossless). Applying the deadband control the proposed algorithm recovers the data such that the first term under the integral is as large as possible within the deadband, whereas the latter one is as small as possible. As a result the passivity condition (3) holds; the communication subsystem is passive rendering the overall system passive and thereby stable.

4. PSYCHOPHYSICAL EXPERIMENTS

Psychophysical experiments are conducted in order to find an appropriate value for p in (1) and (2). The experimental setup consists of two identical 1-DOF haptic displays connected to a PC and a stiff wall as the environment, see Figure 3. 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 including the deadband control are implemented.The velocity/position is communicated to the TOP acting as the set value for the local control loop of the TOP. The TOP tracks the movement of the HSI and communicates back the measured contact force to the HSI as the set value for the force control loop.

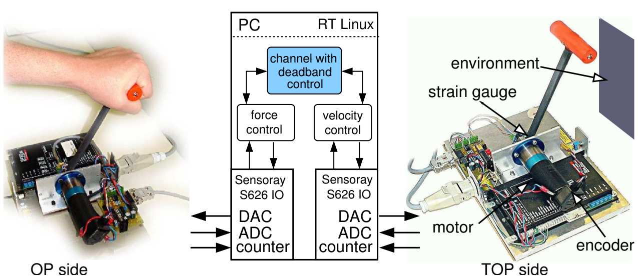

Fig. 3. Experimental setup with two 1-DOF haptic devices

4.1. Subjects

Altogether 14 subjects (aged 20–50) were tested for their detection threshold of the deadband parameter p. There were three female and eleven male subjects one of which was an author of this paper. Only 3 of the subjects had an idea what the distortion the deadband parameter introduces in the system would feel like. Those 3 had also prior contact with the experimental setup. The other eleven subjects did not know what to expect. Only 2 of the subjects had no technical background, all others are engineers. None of the subjects had any impairments of sensorimotor capabilities.

4.2. Procedure

Test subjects sat in front of the HSI lever and were told to operate it with their preferred hand. They were equipped with earphones to mask the sound the device motors generate. The view to the TOP device was blocked so no information could be drawn from the TOP behavior. During a familiarization phase subjects were told to feel the hard contact, a stiff wall by which the lever movement was restricted at the TOP side, through the system with a sampling rate of 1000Hz and without any deadband transmission algorithm applied. As soon as they felt familiar with the system the measurement phase began.

In the experiment detection thresholds for the deadband parameter p 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 p was applied. After each 3 intervals the subject had to tell which of the intervals felt different than the other two. The experiment started with a deadband parameter $p = 2.5\%$ which is unperceivable and was increased after every incorrect answer to 5%, 7.5%, 10%, 12.5%, 15%, 17.5%, 20%, 22.5% and finally 25% which was the highest value tested. When an answer was correct, the same value was used again until 3 consecutive right answers were given. After this first pass, the subjects were told how the distortion feels like and with what kind of technique they should be able to perceive it best. Then the value p was decreased to 2.5% again and successively increased again using the same values and procedure as before. After another 3 consecutive right answers p was reduced by 50% without telling the subjects. After a third pass under the same conditions, the subjects were dismissed. The mean value of the three p values at which the consecutive right answers occurred were taken as the deadband detection threshold for the specific subject.

5. EXPERIMENTAL RESULTS

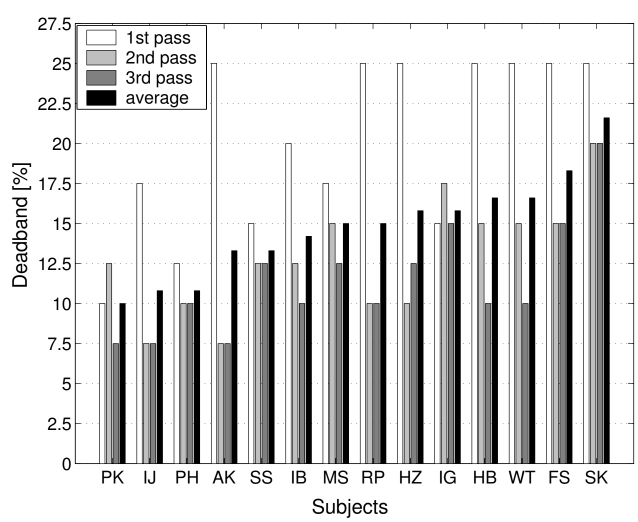

Fig. 4. Overview of the subjects' results

The specific results for every subject can be seen in Figure 4. There are quite a few interesting insights which can be obtained from these results. The first thing that becomes obvious is that almost all subjects had significantly worse detection results in the first pass when they did not know what kind of distortion they had to expect. That leads to the conclusion that the kind of distortion introduced by this deadband approach is not necessarily perceived as disturbing or impairing the contact impression. Some of the subjects even reported that they did not even feel any difference between the undistorted and most distorted signals. Once they were told what the distortion feels like, most of the subjects could improve their detection considerably but no one managed to feel the distortion introduced by the 2.5% and 5% deadband and only very few could discriminate 7.5%. Additionally, most of the subjects reported that although they could feel the distortion it barely disturbed them and that this was the reason why they did not detect it in the first pass.

The main reason for introducing the presented deadband transmission approach is to reduce packet rates on the network connecting OP and TOP. The approach has the potential to achieve this as can be seen in Figure 5, where the average packet rates measured during the psychophysical experiments depending on the deadband values are depicted. The packet rates for velocity packets are already at a one fourth of the non-deadband rate at a deadband size of 10% and keep falling with increasing deadband size. Packet rate characteristics for force packets show an even better behavior. Already at 2.5% deadband we observe a packet rate of under one tenth of the original rate. With rising deadband the force packet rates fall below one twentieth of the rate without deadband.

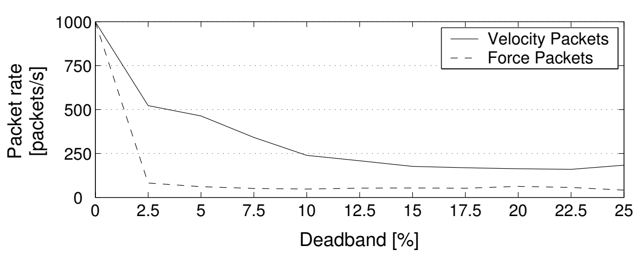

Fig. 5. Influence of deadband on packet rates

6. DISCUSSION AND FUTURE WORK

The proposed deadband transmission algorithm which uses magnitude dependant threshold intervals can significantly reduce packet rates communicated in a telepresence and teleaction system without impairing the fidelity of the system concerning human haptic perception. In case a deadband of 10% is used, which only few subjects could discriminate (and that after learning) and all of them reported as barely noticable and not disturbing at all, packet rates from OP to TOP are reduced to 25%, packet rates from TOP to OP are even reduced to 5% of the original rate.

In this study only the number of packets sent in a TPTA system was subject to optimization. Of course the data itself should be compressed as well. The presented algorithm alone already compresses the communicated haptic data in a lossy fashion by the amount the packet rate is reduced. Due to the nature of the deadband approach a transmitted update value will differ from the last transmitted value by an amount of at least ϵ and will most likely not differ by much more. This leads to a well predictable distribution of possible update values which should be exploitable quite well using efficient entropy coding schemes.

Subject to future work is the further compression of haptic data as well as the extension of the deadband transmission algorithm to TPTA systems that incorporate transmission delay. Application of the algorithm in multi-DOF systems is also planned.

It remains to mention that the presented algorithm is to our knowledge the first approach presented in the literature, which exploits the characteristics of human haptic perception to reduce the data rate of haptic information.

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