Psychophysically Motivated Compression of Haptic Data

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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 forwarded immediately to the receiver which leads to high packet generation rates and high network load especially if the Internet is used as the communication infrastructure. We present multiple approaches to reduce the amount of data communicated in a telepresence and teleaction system. Our new transmission strategies lead to reduced demand on the communication system and therefore more stable communication. The methods presented in this paper range from purely statistical exploitation of haptic data signals to psychophysically motivated compression using a passive deadband transmission approach. The latter only delivers data packets over the network when the sampled sensor data changes by an amount which is just above the human perception threshold. Our psychophysics based approach leads to a considerable reduction (up to 90%) of packet rate and data rate without sacrificing fidelity and immersiveness of the system and has been tested in 1-DoF- and Multi-DoF-Systems.
Keywords. *Telepresence, Teleaction, Data compression, Psychophysics, Haptics*

I. INTRODUCTION

In a telepresence and teleaction (TPTA) system a teleoperator (TOP), typically a robot equipped with different kinds of sensors and actuators, 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 may destabilize 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 [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 strong 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 transmission delay mostly due to congestion in routers appear as well as packet loss.

Current TPTA systems like [2] require fast update rates (500–1000Hz) of 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). Therefore although the payload of haptic data is not very large, the resulting bit rate on the network is considerably larger (50% to 100%). 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 for TPTA applications over the Internet.

In this paper different approaches for data rate and packet rate reduction in TPTA systems are presented. In contrast to the data rate reduction scheme presented in Section 2 where only the statistical properties of the haptic signal are used for compression, the packet rate reduction using a deadband principle (see [3]) described in Section 3 exploits the limitations of human haptic perception. This deadband approach has been thoroughly studied in the 1-DoF case and has been extended to 3-DoFs.

The remainder of this paper is organized as follows. Section 2 shortly presents the compression approach based on signal statistics. In Section 3 we present our deadband transmission approach for a 1-DoF system followed by the extension to the 3-DoF case in Section 4. In Section 5 we present and discuss measurement results for both cases. Section 6 concludes this paper with a brief summary.

II. STATISTICAL APPROACH

Due to the relatively high sampling frequency required for a stream of haptic data, the changes in sample values (positions, velocities, forces etc.) from one sample to the next are relatively small. During operation with the telepresence system presented in [2] the highest measured relative frequency occurs in the case of no pose change (see Figure 1). Such a distribution is well compressible using a DPCM-cased compression scheme. Huffman coding of the differences in sample values allows us to use very short codewords — e.g. 1 bit for the transmission of value 0 — for very frequent values and longer codewords for less frequent values. Despite the significant compression gain achievable, differential encoding leads to a problem in case of packet loss on the channel. The difference values affected by this disruption of the data stream do not reach the destination. Therefore a constant offset would appear in the subsequent reconstructed values. To compensate for this offset, it is necessary to transmit absolute values every n samples.

For haptic data with 16 bit resolution and 500 Hz sampling rate as encountered during operation of the system in [2], the proposed compression scheme reduces the amount of data communicated to about 10% to 25% of the uncompressed rate.

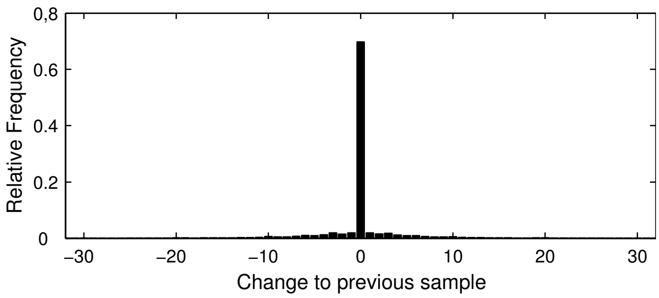

Fig. 1: Relative frequencies of the changes from sample to sample in the TPTA-System presented in [2].

The main reason why this approach is not as efficient as hoped for is the aforementioned packet header to payload ratio of a haptic data stream. Even very good compression on the payload itself is useless if a big share of the necessary network bitrate is caused by packet headers. Therefore, the compression schemes in the following sections aim at packet rate reduction rather than payload compression.

III. DEADBAND TRANSMISSION

A. Psychophysical Background

Human perception has undergone thorough research during the last century. The respective perceptual threshold values for all kinds of stimuli put on the human body have been studied. Apart from very detailed information for every modality a human being can perceive, one major conclusion emerged from these studies: Human haptic perception often follows Weber's Law. Ernst Weber was an experimental psychologist who in 1834 first discovered the following implication

$$\frac{\Delta I}{I} = k \quad \text{or} \quad \Delta I = kI$$

where ΔI is the so called Difference Threshold or the Just Noticeable Difference (JND). It describes the smallest amount of change of an (arbitrary) stimulus which can be detected just as often as it cannot be detected. I is the initial stimulus which is altered by the JND and the constant k describes the linear relationship between the JND and the initial stimulus.

Weber's Law can be generally applied to human perception. It is not always true but still gives a good baseline for stimulus relationships. Further studies [4] tell us that the human haptic perception system follows Weber's Law quite well. The factor k which signifies the magnitude of the change in a stimulus which can be perceived lies mostly between 5% and 15%. This depends both on the type of the stimulus and the limb or joint where it is applied [5].

B. Deadband Principle

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 considerable changes in 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 of only minor changes in the system, 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 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 for stability reasons (see [6]). As a result the deadband approach decreases the packet 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.

B. 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 only be transmitted in case of true motion.

B. 2. Velocity values

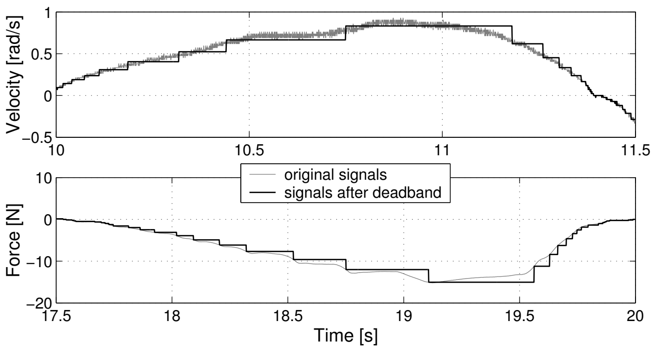

Fig.2: Velocity and force signals before and after applying the proposed deadband transmission algorithm with $p = 0.25$

Based on the aforementioned notion of the JND 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. In this case we are not using a constant ϵ as our threshold value but use

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

instead where p is the percentage of change in velocity which is just not noticeable. This p is determined in psychophysical experiments described in [6]. The effect of the deadband algorithm for velocity is shown in the upper part of Figure 2; the data have been recorded during a test session of a psychophysical experiment. Note the increasing size of the deadband with increasing velocity.

B. 3. Force values

Similar to the section before 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, 7], 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 2 a force plot using our deadband transmission algorithm is shown. The deadband size increases with force magnitude according to the JND for force perception.

IV. EXTENSION TO 3-DOF

In the following we explain the extension of the one dimensional deadband (basically a numeric interval) to two dimensions (where the deadband becomes a circular area) respectively three dimensions, where a spherical volume element serves as deadzone. We denote a multidimensional deadband as deadzone from now on.

To be able to use a deadzone the respective sampled unit has to be represented as a vector. In the following we explain the proposed approach in two dimensions for simplicity reasons. The extension to three dimensions is then straight forward.

In the 1-DoF case the magnitude of the difference d between an initial value v_i and a current value v_c has to be evaluated. This is done by calculating the difference between those two sample values and comparing it to a threshold value p (the deadband multiplied by the initial value v_i).

$$\begin{aligned} d &= |v_i - v_c| \\ d &\leq |p \cdot v_i| \implies \text{Do nothing} \\ d &> |p \cdot v_i| \implies \text{Transmit new value} \end{aligned}$$

In the two dimensional case the scalar variables v_i and v_c become the vectors $\mathbf{v}_i$ and $\mathbf{v}_c$ and the operators become their respective vectorial counterparts. The magnitude of the vectorial difference d, and the deadband p are still scalar.

$$\begin{aligned} d &= |\mathbf{v}_i - \mathbf{v}_c| \\ d &\leq p \cdot |\mathbf{v}_i| \implies \text{Do nothing} \\ d &> p \cdot |\mathbf{v}_i| \implies \text{Transmit new value} \end{aligned}$$

Figure 3 illustrates the 2D deadzone where $\mathbf{v}_i - \mathbf{v}_c$ is the difference vector of the initial and the current vector. The deadzone is depicted as a circle around the tip of vector $\mathbf{v}_i$ with radius $p \cdot |\mathbf{v}_i|$. The angle between $\mathbf{v}_i$ and $\mathbf{v}_c$ is α.

The decision whether to transmit a new value is made as shown in Figure 4.

If the tip of vector $\mathbf{v}_c$ lies within the circular deadzone, the deadband is not violated and thus no new value is transmitted. If the tip lies outside the circular deadzone, updated sample values are sent.

The deadzone having the shape of a circle makes it computationally easy to calculate whether the deadband

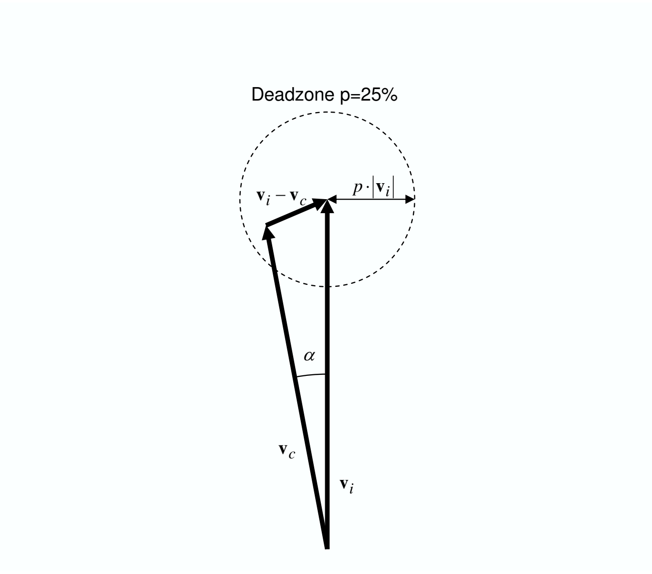

Fig.3: Geometrical description of a 2-DoF deadzone.

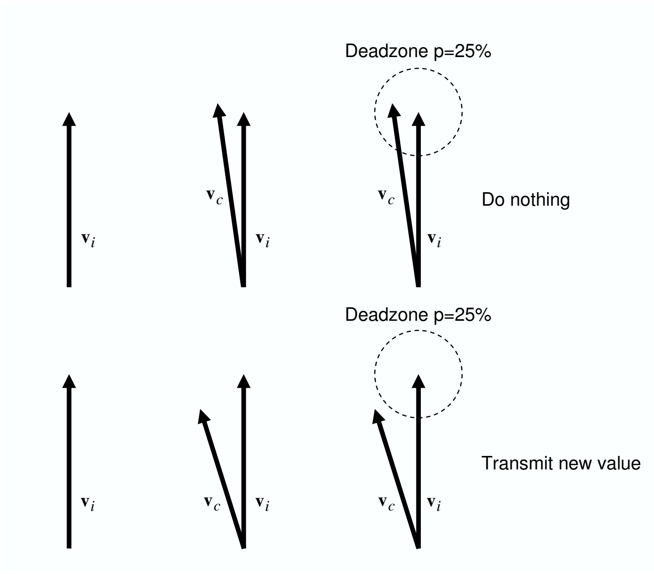

Fig. 4: Criterion for transmission of new values in the 2-DoF case.

was violated or not. Basically the length of the vector $\mathbf{v}_i - \mathbf{v}_c$ has to be compared with $p \cdot |\mathbf{v}_i|$, the length of the initial vector multiplied by the deadband factor p. Depending on the result the respective action is taken just as shown in the equations above.

The extension of this approach to 3D is straight forward. The vectors $\mathbf{v}_i$ and $\mathbf{v}_c$ become 3-dimensional, the circular deadzone becomes a spherical deadzone, in which the tip of $\mathbf{v}_c$ has to lie in order not to trigger an update value. All other calculated values stay the same, because the vectors $\mathbf{v}_i$ and $\mathbf{v}_c$ in any case define a plane in which the above calculations are true.

V. RESULTS

In the 1-DoF case an experiment has been conducted as described in [6]. 14 subjects had to operate a 1-DoF teleaction system numerous times in order to evaluate the detection threshold for the 1-DoF deadband. For this threshold a deadband percentage between 7.5% and 12.5% was determined for both velocity and force.

In the 3-DoF case another experiment has been made using a SensAble Phantom-Omni device which was used to manipulate a virtual environment rendered on another computer in the network. The subjects should give their opinion between 1 and 10 how good a certain compression feels where 1 was the worst and 10 the best grade. In order to get a reference frame they were shown the best case without compression (10 points) as well as the worst case with radical compression applied (1 point) beforehand. After this, they were presented with the same virtual haptic scene with numerous different compression parameters applied. In this experiment deadbands on velocity alone and force alone have been used as well as the combined deadbands. The evaluation shows us that for velocity packets (direction from OP to TOP) up to 20% deadband is allowable whereas for force packets 7.5% should be the threshold.

The main reason for introducing deadband transmission approaches is to reduce packet rates on the network connecting OP and TOP. The approaches have 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.

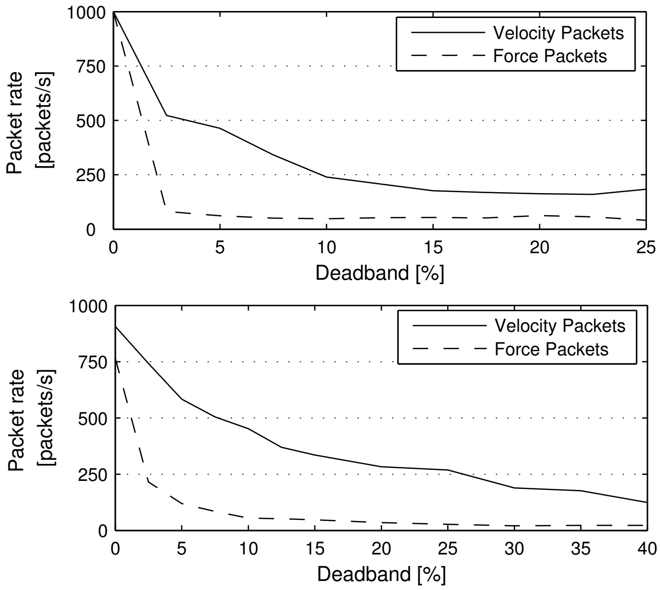

Fig.5: Influence of the deadband on packet rates for the 1-DoF (upper) and 3-DoF (lower) case.

In the 1-DoF case the packet rates for velocity packets are already at one quarter 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 increasing deadband size the force packet rates fall below one twentieth of the rate without deadband.

In the 3-DoF case packet rates are a bit worse in comparison to the 1-DoF case. The force and velocity curves are not decreasing as rapidly as in the 1-DoF case mostly because the 1-DoF experiment consisted of both free space movements and contact situtions whereas in the 3-DoF experiment contact with the environment was experienced at almost 90% of the time. In contact situations velocities are small and therefore the velocity deadband is small as well while forces change almost all of the time.

Even in an almost worst case scenario what haptic compression is concerned as in the 3-DoF experiment we can still observe a good packet rate reduction. Packet rates for velocity packets are reduced by almost 75% when using barely perceivable (based on the given ratings) 20% deadband. For force packets a reduction by almost 90% is possible by chosing the also barely perceivable 5% deadband.

VI. CONCLUSION

The proposed deadband transmission algorithm which uses magnitude dependant threshold zones can significantly reduce packet rates communicated in a telepresence and teleaction system without impairing the fidelity of the system. In case a deadband is used, which only few subjects could discriminate and all of them reported as barely noticable and not disturbing at all, packet rates from OP to TOP are reduced by up to 75%, packet rates from TOP to OP are even reduced by up to 95% of the original rate.

VII. ACKNOWLEDGEMENT

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