

Chapter 2

Perceptual Deadzone

In this chapter, we first review the current literature related to the haptic data compression techniques. Subsequently, we review the concept of using perceptual deadzone for data compression. We review perceptually adaptive sampling strategies and their corresponding deadzones for multidimensional haptic signals. After that the literature related to the effect of rate of change of a stimuli on the Weber fraction is reviewed.

2.1 Haptic Data Compression

In the literature, there is a mention of two types of techniques for haptic data compression: Statistical (Shahabi et al. 2002) and Perception-based approaches (Hinterseer et al. 2008). In the statistical approach, signal properties are used for compression. On the other hand, perception-based approaches exploit the limitations of human perception, and hence remove perceptually irrelevant information from the signal.

Statistical methods use block-based processing and standard signal compression techniques (Hikichi et al. 2001; Kron et al. 2004; Tanaka and Ohnishi 2010; Shahabi et al. 2002) for haptic data compression. In (McLaughlin et al. 2002), the proposed statistical method employs similar approaches that are used in speech coding for compressing the haptic data. The authors apply differential pulse code modulation (DPCM) to develop a low delay coding scheme. In (Shahabi et al. 2002), adaptive sampling along with DPCM is used to compress various forms of haptic data such as rotation, displacement, and force feedback in a virtual environment (VE). This paper also compares the benefits and limitations of a variety of statistical methods in terms of data storage, accuracy, and bandwidth. In (Tanaka and Ohnishi 2010), a lossy compression technique based on the discrete cosine transform (DCT) is used for the compression of haptic packet rate. DCT is an orthogonal transform and there exist several lossy data compression methods based on an orthogonal

transform used in image and audio coding (Sikora 2005; Painter and Spanias 1997). The paper adapts a fast computing algorithm (Lee 1984) for the implementation of the DCT. Experimental results show that the time delay introduced by the proposed method in the loop is predictable and constant, and hence can be compensated using a time delay compensator such as a smooth predictor (Richard 2003). In (Borst 2005), predictive coding is used along with lossy uniform and nonuniform quantizers to reduce the haptic data rate. In (Kron et al. 2004), a differential haptic encoding scheme based on DPCM and a fixed quantization, combined with Huffman coding, is presented. However, all these statistical approaches introduce an additional delay due to the processing of blocks of signal. As mentioned before, unlike audio and video transmission, there exists a global control loop over the communication network for the haptic data transmission. The additional delay introduced by the statistical approaches impairs the stability of the control loop, affecting immersiveness of the telepresence and teleaction (TPTA) system like telesurgery. Hence, these block-based approaches cannot be applied for haptic data compression.

In the recent past, researchers have proposed perceptually adaptive sampling strategies based on the Weber's law of perception for the compression of haptic data (Clarke et al. 2006; Dabeer and Chaudhuri 2011; Hinterseer et al. 2008; Hinterseer and Steinbach 2006; Hinterseer et al. 2005, 2006b; Hirche et al. 2007; Sakr et al. 2009a, b; Steinbach et al. 2011; Vittorias et al. 2009; Lee and Payandeh 2011). According to the Weber's law, the relative change in the signal determines its perceptual value to a user. Hence, in this approach, a stimulus is sampled at time instants where the percentage change exceeds a threshold value called the Weber fraction. Therefore in this approach, only perceptually significant sample points are transmitted, thus avoiding irrelevant sample points from being transmitted. This is a kind of nonuniform adaptive sampling, called as the Weber sampler. In some literature, this method of compression is also termed as the perceptual deadband approach. The Weber's law is also known to hold good for audio and video modalities (Moore 2007b; Brill 1983a; Lennie and D'Zmura 1987). In (Jayant et al. 1993), a detailed survey of application of the Weber fraction for audio and video signal compression is given. In the literature on audio and video compression (Flanagan 1957; Awad and Guerin 1984; Malo et al. 2000; Acharya and Ray 2005), the Weber fraction has been used for nonuniform quantization with the use of uniform sampling. In the above-mentioned literature on perceptual deadzone-based approach, the Weber fraction has been used for the purpose of nonuniformly spaced adaptive sampling.

Results presented in (Hinterseer et al. 2008; Hinterseer and Steinbach 2006) show that the haptic data rate can be reduced by up to 90% using this approach, without affecting the immersiveness of the TPTA system. In order to compress the haptic data rate further, in (Hinterseer et al. 2006a), a model-based predictive coding is proposed along with the perceptual deadband approach. A signal predictor is used on both sides—operator and teleoperator (TOP) of the system. On the operator side, the predictor estimates the future force samples coming from the TOP side. The same predictor used on the TOP side makes sure that whenever the predicted sample differs from the actual value more than the just noticeable difference (JND), a new sample is sent to the operator side. This paper implements a simple first order linear

predictor. In order to calculate the slope of the predictor, it employs the latest two perceived/transmitted samples and their corresponding time stamps. In order to utilize the predictor at the operator (OP) side, the slope of the predictor, the last perceived sample along with its time stamp is transmitted to the operator side. To analyze the model, a psychophysical experiment is performed for various values of the Weber fraction ranging from 0 to 40%. This method has been implemented for both velocity and force samples. Experimental results show that linear prediction improves the accuracy of the perceptual deadzone approach and the packet rate can be reduced by up to 95% without affecting the immersiveness of the system.

In (Hinterseer et al. 2006b), fast Kalman filters are used to reduce the noise in the signal before applying the prediction-based perceptual deadband approach mentioned in (Hinterseer et al. 2006b). This pre-filtering step makes signal prediction easier and more accurate. Results show that the Kalman pre-filtering step improves the accuracy of the prediction-based deadband approach considerably. The proposed Kalman pre-filtering step works well for both velocity and force data. In (Brandi and Steinbach 2013), linear regression-based predictors are proposed for improving the prediction of the haptic samples. As an alternative to the Kalman filtering for removing the noise in the signal, it also proposes a moving average (MA) filter. Experimental results show that for both velocity and force signals, regression-based predictors reduce more packets in comparison to the linear predictor.

In (Clarke et al. 2006), in order to compensate for the network delay, motion prediction is proposed along with the prediction-based perceptual deadband approach. The authors use a motion predictor on the operator side which predicts the position and velocity of the haptic interface point before transmitting them to the teleoperator (TOP) side. A doubly exponential smoothening prediction algorithm (Massie and Salisbury 1994) is used for motion prediction and the root mean squared error (RMSE) is used for the analysis of its performance. In order to demonstrate the results, a psychophysical experimental setup is designed where the Phantom Desktop haptic device is used as an operator and the teleoperator scenario is implemented virtually.

In (Sakr et al. 2009a), two prediction-based perceptual deadband approaches are proposed for haptic data reduction and transmission in telementoring systems. In case of telementoring system, one experienced user mentors another user/trainee over a network while incorporating the haptic modality. Due to its adaptability to different learning scenarios, the telementoring system is different from a typical teleoperation task. The first approach computes the Weber fraction of the perceptual deadband approach while computing the velocity of the user's hand velocity whereas the other approach computes that with respect to the user's hand position. The prediction model used in the paper is supported by the least-squares method and a median filter to reconstruct the unsuccessfully received samples. Experimental results show that the proposed approaches reduce the haptic packet rate by nearly 96%.

In (Lee and Payandeh 2011), a modified perceptual deadband approach is proposed. The modified deadband approach consists of a contact force detector, a quantizer, and a force predictor. In case of a teleoperation scenario, the contact force is generated only when the teleoperator or virtual teleoperator interacts with a real or

virtual environment. If there is no interaction, a zero force should be rendered at the operator side. Hence, to improve the performance of the deadband approach, a contact force detector is included which makes sure that the force predictor is bypassed in case there is no interaction and a zero force is rendered. This paper compares a fixed rate down sampler, linear prediction-based deadband approach and the modified deadband approach. It introduces an operational rate distortion performance measure to evaluate the performance of these methods. Experimental results show that the prediction-based deadband approach compresses the data rate more than the fixed rate down sampler. The modified deadband approach further improves the reduction in haptic packet rate. In (Dabeer and Chaudhuri 2011), a theoretical analysis of the Weber sampler has been carried out and it has been shown that the Weber sampler or the perceptual deadband approach may result in an arbitrarily large number of samples due to finite precision representation of sample values when applied on a finite interval of time even for simple cases. In order to avoid this situation, the authors include a regularizer term in the structure of the Weber sampler. This regularized Weber sampler has been analyzed for both smooth deterministic and stochastic signals. The paper computes the average number of samples to be transmitted and the inter-sample time based on the regularized Weber sampler.

In (Zadeh et al. 2008), the authors have proposed a method to measure the force thresholds (JND) with respect to the user's hand motion. Thus, it studies the effect of velocity on force perception. It is observed that as the user's hand velocity increases, the just noticeable difference increases. The proposed method can be used for haptic data compression where there is a relative motion between the user and the object. As per this method, fewer details need to be transmitted when the user's hand is in motion.

In (Schuwerk et al. 2016), the authors have used the aforementioned perceptual deadband approach for the compression of 3-D polygon mesh deformation data for a distributed client-server (CS) architecture with simulated deformable objects. In the CS architecture, the server receives the device position from the client, and calculates the polygonal mesh deformation using physics-based simulations. Then, it transmits the mesh deformation data to the clients to update the local copies of the haptic virtual environment (HVE). As the number of vertices in the polygonal mesh increases, the deformation data (in terms of the bit rate) to be transmitted from the server to the clients grows. Thus, it is required to compress the deformation data while maintaining a realistic simulation of deformable objects. The authors have used the haptic perceptual threshold for the compression purpose. The deformations which are not perceivable by a human being, are not transmitted to the clients. Results based on objective and subjective evaluations show that the proposed method helps in achieving a compression ratio of 11:1, while maintaining the haptic distortion below the human perceivability. The perceptual deadband approach has also been used for the compression of tactile stimuli. In (Tirmizi et al. 2016), the authors have applied the deadband approach for cutaneous haptic feedback. Results show that the compression scheme based on the perceptual threshold reduces the cutaneous data rate by 61.7% while maintaining the quality of perception.

There have been several control architectures studied in (Anderson and Spong 1989b; Cho and Park 2005; Hashtrudi-Zaad and Salcudean 2001; Niemeyer and Slotine 1991; Kuschel et al. 2006) to enable telepresence applications in presence of a significant time delay. Scattering theory (Anderson and Spong 1989b), in particular, is one of the architectures used for stabilizing the global control loop in presence of constant time delay for a TPTA system. In this approach, wave variables are transmitted, instead of the haptic signals. A wave variable is a linear transformation of haptic signals (velocity and force). Since wave variables do not directly represent the haptic signals, it is not known whether the Weber's law can be applied on the variables defined in the wave variable domain. Hence, the perceptual deadband approach is not directly applicable in the wave variable domain. To solve this issue, in (Vittorias et al. 2009), an approach is proposed that combines both the perceptual deadband approach and the wave variable approach for the reduction of the haptic packet rate while maintaining the stability of the global control loop for a time delayed teleoperation. In the proposed method, perceptually encoded haptic signals are transmitted, instead of wave variables, while utilizing the stability property of the scattering theory. The proposed approach is named as locally computed wave variable (LCWV) deadband approach. The method has been evaluated through simulation studies on the basis of packet reduction rate and the stability of the loop.

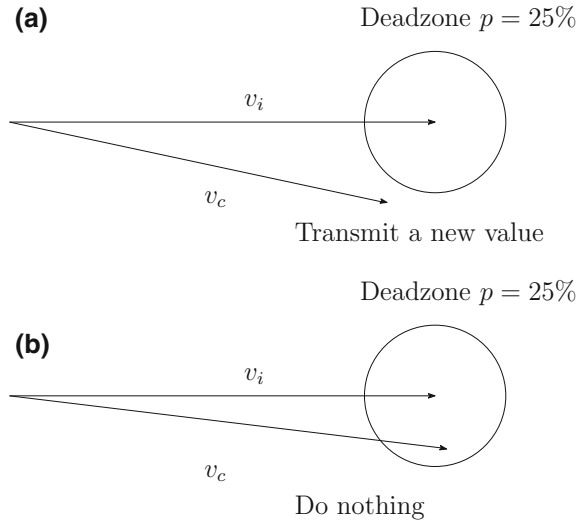
The work in (Gokhale et al. 2016b) proposes an opportunistic adaptive sampling technique for haptic signal to dynamically adapt the data rate on a shared network. The algorithm uses Weber fraction as the control parameter for tuning the number of haptic sample transmissions to match the fluctuating network conditions. For example, when the network has bandwidth available the Weber fraction is reduced to transmit a high fidelity haptic signal. On the other hand, during congested network conditions the Weber fraction is set to the maximum admissible value to curtail the haptic data rate.

2.2 Perceptual Deadzone for Multidimensional Signals

Most of the studies about the perceptual deadzone approach mentioned above are used for the reduction of haptic data rate for one-dimensional haptic data. In order to apply the perceptual deadzone approach for the compression of multidimensional haptic signals, it should be known what is the correct structure of the Weber deadzone for these kinds of signal since it captures the perceptual limitations of a human being. The Weber deadzone is defined by the Weber fraction. It should be determined whether the Weber fraction depends on the direction of the applied haptic force or not. There are a few studies done in the literature which address these issues. In this section, we review these studies.

In (Hintseer and Steinbach 2006), limitations of the 1-D perceptual deadzone approach are addressed when it is extended to deal with multidimensional haptic signals. If we extend 1-D perceptual deadband approach to multidimensional haptic signals, then every single component of the Cartesian representation of the signal

Fig. 2.1 Illustration of the perceptual deadzone approach for two dimensional signal. (Adapted from Hinterseer and Steinbach (2006))



is compared with its respective deadzone. Even if any of the Cartesian components of the signal exceeds its respective deadzone, irrespective of the variations in other components of the signal, the haptic signal needs to be updated/transmitted. This approach does not serve the purpose of reducing the packet rate well. The paper proposes a perceptual deadband approach for multidimensional haptic force signals. In the multidimensional case, the signal is represented as a vector. According to the proposed approach, if the Euclidean distance between the current vector to be transmitted and the previously transmitted vector exceeds a deadzone parameter, the current vector will be transmitted/updated. Let v_c represent the current vector and v_i represent the previously transmitted vector, and $d = |v_i - v_c|$ represents the Euclidean distance between them. If d is greater than a deadzone parameter p , which is a scalar quantity, v_c will be transmitted. This is illustrated in Fig. 2.1 for 2-D signals for a deadzone parameter $p = 25\%$. The proposed approach provides a circular deadzone for 2-D signals. The radius of the circular deadzone is a function of the last transmitted signal vector. This approach can be extended to 3-D signals also. In that case, the deadzone will be spherical. According to this approach, the Weber fraction is the same for each Cartesian co-ordinate of the signal, i.e., the Weber fraction along the X axis is equal to that along the Y axis, avoiding any dependency on the direction of the signal on the Weber fraction.

When we extend the perceptual deadzone approach to the multidimensional signals for data reduction, a new question arises as regards the structure of the perceptual deadzone. To study the structure of the deadzone for multidimensional signals, it is desired to understand the perceptual limitations of a human being with regards to the force direction. There has not been much study available on the Weber fraction/minimum discrimination threshold (JND) for the force direction. In (Barbagli et al. 2006), the discrimination threshold for the force direction is found to be 25.6° , when the magnitude remains the same. The paper also finds that a simultaneous

visual display reduces the threshold to 18° . However, the average visual discrimination threshold for the vector directions is only 3.25° (Barbagli et al. 2006). Hence, considering this, the force direction discrimination threshold appears to be quite poor. In (Tan et al. 2006), it is studied whether the force direction discrimination threshold is independent of the reference force direction or not. The authors claim that it is independent of the reference force direction and its average value is found to be 33° . Based on this study, it is meant that the Weber's law does not hold true for the force direction when the magnitude remains unchanged. In (Elhajj et al. 2006), perception of human force direction is studied in details. The authors state through experimental results that the force direction is perceived more accurately between 60° and 120° region than in other regions, and hence, the force direction perception is not uniform.

The method proposed in (Hinterseer and Steinbach 2006) for multidimensional signals considers only the force magnitude, not the force direction, in determining the structure of the corresponding deadzone. In (Pongrac et al. 2006), both force magnitude and force direction are combined to examine the shape of the deadzone for multidimensional signals. It is studied whether the force direction influences the Weber fraction/JND or not. In order to perform this study, the authors consider three reference stimulus magnitudes ($1N$, $1.5N$, and $2.0N$) and eight perturbation directions (0° , 45° , 90° , 135° , 180° , 225° , 270° , 315°). The comparison stimulus is obtained using a vectorial addition of the reference vector and a perturbation vector. The perturbation vector is applied along the perturbation direction and its magnitude is determined in terms of a percentage b of the magnitude of the respective reference vector. In order to find the structure of the deadzone, the authors perform a classical psychophysical experiment where the JND for any change along each perturbation direction is computed with respect to each reference force stimulus vector. In Table 2.1, the JND along each perturbation direction is shown for the magnitude of each reference force stimulus for two-dimensional signals, and hence a structure of the deadzone is arrived at. The deadzone for a reference stimulus magnitude $1.0N$ is different from that of two other reference force stimulus magnitudes because the Weber's law hardly holds good for lower range of the force stimulus. For perturbation directions 0° and 180° , any change in the perturbation vector only changes the force magnitude and the force direction is unchanged, hence this case is similar to the 1-D signal. The JND shown in the Table 2.1 for both these perturbation directions matches with that found for one-dimensional signals in the literature. For other perturbation directions, the JND is dependent on the combination of the force magnitude and the force direction, due to which the JND gets increased, and hence more compression in the haptic data rate can be achieved. The proposed method signifies that the force direction plays a significant role in determining the structure of the perceptual deadzone for the multidimensional signals. However, authors could not come to the conclusion about the shape of the deadzone as this needs to be studied for more number of reference force stimulus magnitudes and perturbation directions. In (Drösler 2000), the author uses both the force magnitude and direction to define the Weber's law for vector data theoretically. But this study also does not come to the conclusion of the shape of the perceptual deadzone for the multidimensional haptic signals.

Table 2.1 JNDs as a function of the perturbation direction as proposed by (Pongrac et al. 2006)

Reference vector magnitude	JND along perturbation direction			
	0°, 180°	45°, 315°	90°, 270°	135°, 225°
1.0 N	10.0	30.0	24.5	24.5
1.5, 2.0 N	10.8	22.6	20.4	20.4

2.3 Effect of Rate of Change of Kinesthetic Stimuli

In any telehaptic operation, the generated force varies continuously based on the interaction pattern. In all studies on perceptual deadzone approach reviewed above, it has been assumed that the Weber fraction (threshold) of an individual is always fixed and is independent of the nature of the temporal variation in the stimulus. A question does arise about the correctness of the assumption. If the assumption is incorrect, one may either remove some of the perceptually relevant bit stream from the data, jeopardizing the user interaction during teleoperation, or send bit streams which are perceptually irrelevant.

The perceptual limitations of a human being are not fully exploited by the fixed Weber fraction. If the signal changes very slowly, the user tends to forget the reference force, and gets accustomed to the change. Hence, for slowly varying signals, a user faces difficulty in perceiving the difference in the force stimuli. If the signal changes too fast, the user may not be able to react to the change because, in principle, he/she requires about 300 ms (Bhardwaj et al. 2013) to react to a change in the signal. Therefore, the fixed Weber fraction will contribute perceptually inessential packets for such kind of signals. Hence, it is important to examine how the Weber fraction is affected by the rate of change of the kinesthetic force stimuli. Interestingly, to the best of our knowledge, this has never been investigated for kinesthetic force perception.

We notice that this issue (effect of rate of change on the Weber fraction) has been studied for temperature sensing. In (Kenshalo et al. 1968), the authors study the effect of rate of change of temperature upon warm and cool thresholds of the skin when the temperature of the skin of the forearm is maintained at the normal level. The rate of change of stimulus (temperature) is varied between 0.01° and 0.3° C/s. It is observed that the warm and cool thresholds rise at the small rate of change of temperature, and these are not affected after a particular value of the rate of change of temperature (0.1° C/s), as illustrated in Fig. 2.2. Thermal adaptation of the skin is the reason given by the authors for increase in the threshold at slower rate of change of temperature. They also observe that the warm thresholds are influenced more than the cool thresholds at the small rate of change in temperature. Hence, it signifies an asymmetry between the two cases.

Several authors have studied the just noticeable difference (JND) for variations in tempo in speech and music. Tempo is about the rate of speaking and it varies among and within speakers. If a speaker changes the rate of speaking (tempo) during

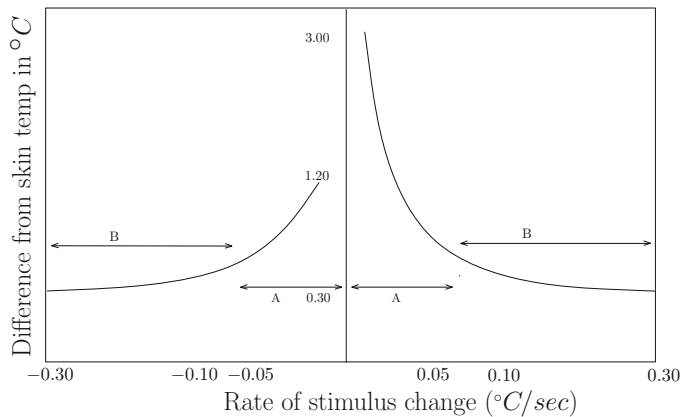


Fig. 2.2 Variation of warm and cool thresholds with respect to the rate of change of the temperature is plotted here (Adapted from Kenshalo et al. (1968)). Region A corresponds to slowly varying stimulus when the JND is computed to be quite high and does vary significantly. In region B when the rate of change is high, the JND is smaller and is not much affected by any further change in the rate of change of stimulus. The curves in the first quadrant corresponds to increase in temperature (used for measuring warm threshold) while the one in second quadrant refers to the cooling phenomenon (used for measuring cool threshold)

the communication, then what is the range of change in tempo so that it becomes perceptually relevant? For music perception, this issue has been addressed in (Ellis 1991; Drake et al. 1992; Levitin and Cook 1996) and the JND for the musical tempo change is found to be in the range of 6 to 8%. In (Quené 2004), it has been studied for speech communication and is found to be about 10%. In (Madden 1998), the author studies the sensitivity of the subjects to rate of change of signals (frequency) and estimate the Weber fraction which is found to be in the range of 0.05–0.06. In (Thomas 2007), it is studied whether the Weber's law hold true for the perception of tempo change. For that purpose, the author performs an experiment where there are two independent variables: *beginning tempo* (i.e., base tempo with respect to which JND is measured) and the *direction of change*. Each independent variable has two levels: beginning tempo-slow (43 beats per minute), fast (75 beats per minute); direction of change: increasing tempo (up), decreasing tempo (down). The user is exposed to four listening conditions: slow-up, slow-down, fast-up, fast-down and is asked to respond to the change verbally whether the reported change is in the increasing way or decreasing way. The just noticeable difference for tempo change is measured in terms of bpm (beats per minute). Statistical results show that the JND for the fast tempo is significantly different from that for the slow tempo for both the directions of change. However, the Weber fraction for the fast tempo matches with that for the slow tempo for both directions of change, and is found to be 8%, hence signifying the presence of Weber's law in the perception of tempo change. Results of this study matches with that mentioned in (Ellis 1991; Drake et al. 1992; Levitin and Cook 1996). However, all the studies mentioned above are related with the Weber

fraction for rate of change of a signal (tempo). But it is not studied how does the Weber fraction for tempo change get affected if the required change (threshold) in the tempo happens very slowly. In other words, here tempo itself is the stimulus and the variation in tempo is not the subject matter of the experiment. We do not find enough literature in any other domains which might have studied the effect of rate of change of the stimuli on the Weber fraction of the corresponding stimuli.

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