On the Impact of Haptic Data Reduction and Feedback Modality on Quality and Task Performance in a Telepresence and Teleaction System*

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Abstract. The perceptual deadband (PD) data reduction scheme allows for a significant reduction of network load in real-time haptic communication scenarios. Aiming to ascertain how the optimum PD data reduction parameter k is best determined, an experiment was conducted in which a possible interaction of PD data reduction and visual feedback on haptic feedback quality and task performance was investigated. The results show that when haptic feedback is complemented with visual feedback, haptic data reduction affects haptic feedback quality at a lower data reduction rate than it affects task performance. When visual feedback is missing, however, this effect is reversed. These results imply that the perception of haptic feedback quality is markedly influenced by visual sensory input as well as task requirements; hence, it is recommended to consider feedback quality and task performance in the optimization of PD reduction before such schemes may be applied to industrial telepresence and teleaction systems.

Keywords: Perceptual data reduction, deadband approach, haptics, lossy compression, task performance.

1 Introduction

Telepresence and teleaction (TPTA) systems allow a human user to operate in environments that are physically distant, hazardous, scaled, or otherwise inaccessible (e.g. virtual) [1]. Specifically, in these systems, a human operator controls a teleoperator, typically a robot equipped with sensors and actuators, via a communication link [1]. In recent years, much research has focused on the added value of haptic feedback for task performance in TPTA systems [e.g. 2,3]. Here, mainly data regarding positions, angles, velocities, forces and torques are transmitted, which present high requirements

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with respect to packet rate/signal update rate, time delay, and delay jitter [4]. When the remote teleoperator is accessed via a packet-based communication network (e.g. the Internet), minimizing the end-to-end delay with the goal of preventing instability of the involved control loops results in high packet rates. In this context, the integration of the perceptual deadband (PD) data reduction scheme proposed in [5] promises a significant reduction of packet rates without impairing the user experience. In contrast to early data reduction techniques [e.g. 6,7], which focus on the exploitation of statistical properties of the haptic signal, the PD data reduction approach exploits limitations of human haptic perception in order to keep introduced coding artifacts below haptic perception thresholds. For PD data reduction, sampled values are only considered to be relevant for transmission if they exceed the operator's just noticeable difference (JND) threshold as defined by Weber's Law [8].

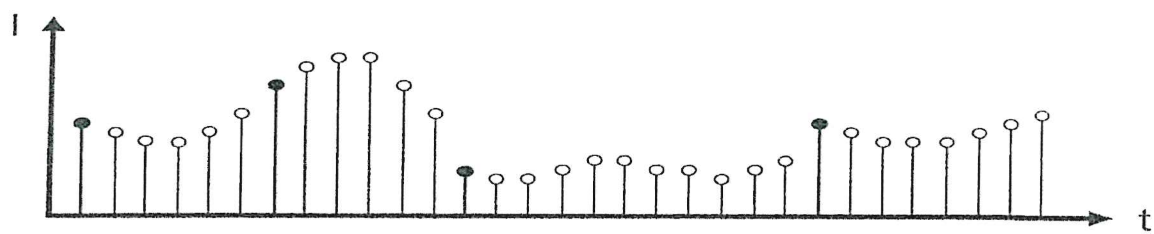

Fig. 1. Principle of the PD approach. Black samples violating the applied perception threshold (grey zones) are transmitted, grey samples are discarded. The perception thresholds are a function of the haptic stimulus intensity.

Hence, only if the difference between the most recently sent haptic signal value and the current input value exceeds an assumed perception threshold, a new transmission of a signal update is triggered. The receiver reacts to a missing sample by holding the value of the most recently received sample (see Fig. 1.). The size of the perception threshold describes the implication $\Delta I = kI$, where ΔI defines the JND threshold and k represents the Weber threshold parameter. Since the optimum amount of haptic data reduction in this approach is directly linked to human force perception thresholds, it is crucially important to ascertain which factors affect the user's perception of haptic feedback and to what degree these findings generalize to various TPTA-systems and –settings before this reduction scheme is employed in industrial settings.

1.1 Previous Work

The PD data reduction approach has been experimentally evaluated in a number of real-world and simulated TPTA systems. Previous work [5] reports force packet rate reductions of up to 85% for a 1-Degree-of-Freedom (DoF) TPTA system. Even higher reduction rates of up to 90% were reported for the multi-DoF extension of the PD data reduction approach [4].

Whilst the PD data reduction approach was found to be very successful in reducing network load, when it comes to the practical implementation of this approach in TPTA systems, the question remains, how the optimum Weber threshold parameter defining the size of the PDs may best be determined. Although, in theory, JNDs for force magnitude are approximately similar for all healthy human operators [9], configurations for the parameter k reported in the literature vary widely. For example, [5] found a threshold for the detection of PD-induced coding artifacts in the haptic signal of around k=2.5-7.5%, whereas [10] found no significant feedback quality deterioration with PD parameters of k<=15% and [11] reported thresholds to range between k=7.5% and k=20%. This suggests that the optimum size of the PD approach is not determined by a single JND of force magnitude, but influenced by various other factors as well. For instance, it seems reasonable to assume that detection thresholds of PD-induced coding artifacts are highly dependent on the system characteristics of the TPTA system used, as was suggested by [10]. In addition, cross-modal interactions, particularly those pertaining to visual sensory input, were also found to affect force perception JNDs [12], suggesting that haptic PD thresholds may also be influenced by the type of visual feedback received.

Finally, previous experiments were conducted in telepresence scenarios without consideration of contact force intensity. However, in many telepresence application scenarios such as dealing with dangerous materials or touching fragile objects, accurate representation of small contact forces is likely of great perceptual importance to the user. Hence it seems plausible that the characteristics of the haptic feedback signal, and consequently the effects of PD-based data reduction, strongly depend on the applied TPTA scenario. In this context, the threshold criterion in determining optimum PD sizes is also likely to make a difference. For example, until now, most studies on PD data reduction focused exclusively on the transparency of the applied signal processing steps in determining optimum PD detection thresholds [e.g. 5,11]. The rationale behind this approach is that as long as a loss of data is not noticeable, task performance should not be affected. However, as of yet, too few studies systematically investigated the effects of haptic PD data reduction on task performance so as to justify such a claim. For future applications of PD data reduction to specific TPTA systems it is therefore important to ascertain if and in what way task performance deterioration is linked to subjective impressions of the haptic feedback quality of TPTA systems and how this link might be influenced by other feedback modalities.

1.2 Research Questions

Based on this rationale, the present study aimed to systematically investigate the effects of PD data reduction on the perceived quality of haptic feedback and task performance in a TPTA scenario simulating a safety-critical application, in which minimal contact force is expected due to careful teleoperator navigation. Finally, it was to be investigated whether the effects of PD data reduction on task performance accuracy and/or perceived haptic feedback quality depend on the type of feedback employed. Specifically, since with visuo-haptic feedback, vision typically dominates the perceptual focus [e.g. 12], the present study aimed to establish whether the effects of PD data reduction on the experimental measurements would change if the perceptual focus was shifted to the haptic modality as visual feedback is withdrawn.

2 Methodology

2.1 Participants

A convenience sample of 13 female and 29 male (N=42) participants, aged 21-50 yrs. (mean age: 30.64 yrs., std. dev.: 7.22 yrs), took part in this experiment, all of whom were right-handed. A standardized motor performance test (Motor Performance Series© by Dr.G. Schuhfried GmbH) ensured that none of the participants were impaired in their tactile perception or motor performance.ï

2.2 Experimental Design and Setup

An 11 (PD parameter) x 2 (feedback modality) mixed-subjects design was employed, with PD data reduction as a within-subjects variable, which was manipulated on 11 levels (k=0%; 5%; 10%; 20%; 30%; 40%; 50%; 60%; 70%; 80%; 90%). Participants were assigned to one of two groups: one group received visuo-haptic feedback from the TPTA environment, the other performed with haptic feedback only. The groups were balanced in terms of gender, age and motor ability. Measured were data reduction performance, task performance defined as force control (variance in surface penetration depths and maximum surface penetration distances), as well as perceived haptic feedback quality. A Phantom Omni haptic device by SensAble Technologies™ was used for the experimental main task. For this task, participants were asked to move their cursor from a starting point through a three-dimensional, haptically rendered tunnel, to a pre-specified target position. The simulated stiffness of contact with the virtual tunnel was set to 15 N/m.

2.3 Procedure

Participants were naïve to the purpose of the experiment; they were merely told that "different settings of the Phantom device" would be tested. Participants were given the opportunity to familiarize themselves with the apparatus and the virtual environment without task performance constraints. They were then provided with standardized instructions asking them to traverse the virtual tunnel, while keeping in contact with its ground surface at all times with as little pressure as possible. Before main trials, participants underwent a stringent, methodical practice phase which had been established based on rigorous pilot testing. Purpose of this practice phase was to ensure that all participants performed the experimental task in a somewhat consistent manner so that measured variations in task performance could be confidently attributed to the experimental manipulation rather than individual style. Each person then performed the main task 11 times, each time at a different stage of PD data reduction, whereby the PD parameters were presented in randomized order to avoid practice and order effects. After each trial, participants rated haptic feedback quality.

3 Results

Possible differential PD data reduction effects of feedback on the data update rate, subjective haptic feedback quality and force control measures were investigated by conducting analyses of variance (ANOVA) for each feedback group, i.e, the group which had received visuo-haptic feedback and the group which had received haptic feedback only, individually. In cases where the assumptions for parametric tests had not been met, appropriate corrections were applied or non-parametric tests were used, as is specified in the following.

3.1 Data Reduction Performance

For both groups, the largest reductions in the number of sent data packets per second were observed for PD parameters of k>=20%. Figure 2 displays the median values for sent signal updates for each feedback group against the median values for force control measures.

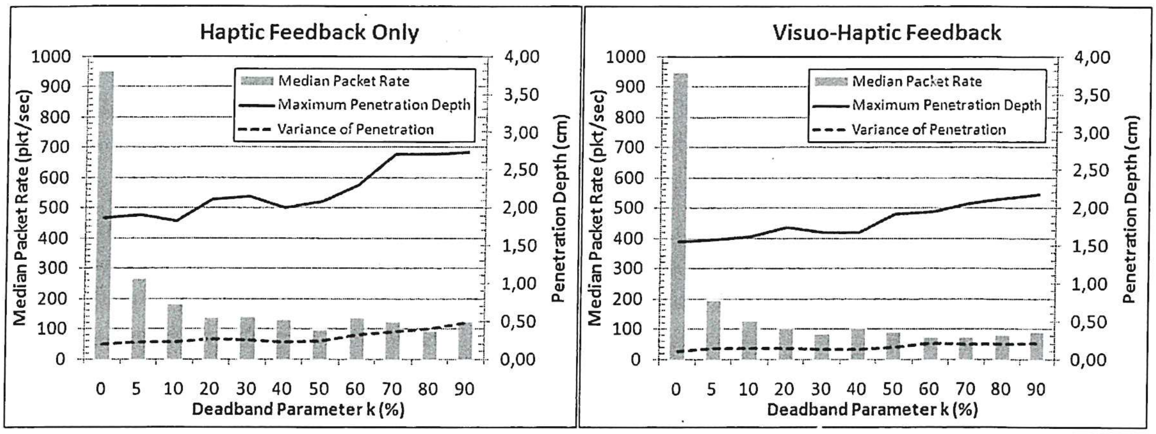

Fig. 2. Median number of data packets sent per second, penetration variance and maximum penetration depth for each PD parameter in each feedback group

3.2 Perceived Haptic Feedback Quality

Perceived deterioration of the haptic feedback quality was measured with a single 20-point Likert-type scale ("To what degree, if at all, did you perceive a disturbance in the haptic feedback") ranging from 1 (no disturbance was felt) to 20 (extremely large disturbance was felt). For the visuo-haptic feedback group, a parametric ANOVA revealed a significant deadband main effect on the quality of haptic feedback (F(4.56, 91.24) = 17.19, p<.001) (with Greenhouse-Geisser Correction, $\varepsilon = 0.46$), indicating that disturbance ratings differed significantly with different PD parameters. A similar effect was found for the haptic feedback group (F(4.69, 93.82) = 5.93, p<.001) (with Greenhouse-Geisser Correction, $\varepsilon = 0.47$). Bonferroni-adjusted post-hoc simple contrasts of disturbance ratings in each PD condition to the baseline (k=0%), revealed no sig. difference in disturbance ratings up to k=30% for the visuo-haptic group (F(1,20)=10.47, p<.005, part. η^2 =.34), and even up to k=80% for the group which only received haptic feedback (F(1,20)=11.47, p<.005, part. η^2 =.36).

3.3 Task Performance

Since one of the main purposes of haptic feedback is the intuitive control of forces applied to surfaces, penetration of the virtual tunnel's surface was deemed an appropriate measure of task performance accuracy. Here, two measures were considered: the variance in penetration depth and the maximum distances that participants penetrated into the surface, both measured in haptic device workspace scale (cm).

Surface Penetration Variance. With data of the haptic feedback group, Friedman's ANOVA showed a sig. effect of PD data reduction on penetration depth variance ($\chi^2(10)=61.53$, $p<.001$). The ANOVA also confirmed this effect on penetration variance for the visuo-haptic feedback group ($\chi^2(10)=33.92$, $p<.001$). Following-up the significant PD effect, Bonferroni-adjusted post-hoc signed-rank Wilcoxon comparisons of the measurements in each PD condition to the baseline measurement (k=0%) were made. For the haptic feedback group, none of the comparisons met the adjusted p-acceptance level of $p<.005$ up to a Deadband of k=60% ($z=-3.04$, $p<.005$, $r=-.47$) and above. For the visuo-haptic feedback group, the comparison to the baseline was significant at k=70% ($z=-3.14$, $p<.005$, $r=-.47$) and above.

Maximum Surface Penetration Depth. Friedman's ANOVA conducted on the maximum surface penetration distances for each feedback group individually confirmed sig. PD effects for both the haptic ($\chi^2(10) = 67.20$, $p<.001$) as well as the visuo-haptic feedback group ($\chi^2(10) = 43.76$, $p<.001$). Follow-up Bonferroni-adjusted Wilcoxon comparisons to the baseline condition (k=0%) showed a sig. difference in maximum surface penetration distances for k=60% ($z = -3.04$, $p<.005$, $r=-.47$) and above for the haptic group and for k=50% ($z = -3.30$, $p<.005$, $r=-.50$) and above for the visuo-haptic feedback group.

4 Discussion

Previous studies on PD data reduction focused on the transparency threshold of the applied signal processing routines. The underlying assumption was that as long as a loss of haptic information is not detectable, PD data reduction would not have a noticeable effect on the operator's control of the teleoperator. Aiming to ascertain how the optimum PD parameter k is best determined, the present study was conducted to investigate the performance of perceptual deadband coding with respect to perceived haptic feedback quality and force control as a measure of task performance. Furthermore, it was investigated whether these effects of haptic data reduction are influenced by visual feedback, or lack thereof.

The results show that, overall, the PD data reduction effects on task performance do not seem to change when the perceptual focus is shifted to the haptic modality, as similar thresholds, i.e. between k=50% and k=70%, are found for the force control measures of maximum surface penetration depth and penetration variance for both feedback groups. Interestingly, the detection thresholds varied widely between the two feedback groups. Participants who received visuo-haptic feedback from the task environment were more sensitive (threshold at k=30%) to the deteriorative effects of

PD data reduction than were those in the haptic feedback condition (threshold at k=80%). Presumably, participants who lacked this visual source of information were less able to distinguish coding artifacts from the intended haptic rendering, even though a stringent practice phase, in which PD data reduction was not applied, ensured that participants were familiar with the actual haptic rendition of the task environment. These results differ greatly from detected transparency thresholds in previous experiments. In contrast to previous PD-related experiments, in the present study, an application scenario was evaluated where small contact forces are expected. It seems that in TPTA scenarios with small expected contact forces, the artifacts introduced by PD data reduction are less disturbing as force-feedback intensity stays within small bounds.

For the implementation of PD-based haptic data reduction, the results indicate that the point of data reduction detection does not necessarily stipulate the on-set of task performance deterioration, at least not with respect to task performance criteria that relate to the operator's control of forces. Depending on the availability of additional feedback sources, data reduction may not even be consciously detected, even though the operator's control of the teleoperator is measurably affected. Furthermore, considering PD detection thresholds reported in the literature vary widely, this research clearly suggests that there is no single optimum PD threshold which may be universally applied to all TPTA-systems, but rather that its implementation into these systems needs to be adapted to the systems' capabilities and environmental demands, including specific task performance criteria.

On a final note, it should be mentioned that, concurring with previous studies on the PD data reduction approach [e.g. 5,10,11], the present study confirmed the effectiveness of this lossy data reduction scheme in terms of data reduction performance. In fact, for the specific set-up of the present study, an analysis of the packet rate reduction showed that PD parameters of k=10% already translated into packet rate reductions of 81% and 87 % with haptic feedback and visuo-haptic feedback, respectively, without significantly affecting perceived haptic feedback quality or operator force control. Further research is needed to investigate if and to what extent the findings of the present study generalize to other TPTA systems. In particular, a systematic investigation of the influence of limitations in mechanical bandwidth of deployed hardware components is needed. In addition, further evaluative studies are recommended which compare the PD data reduction approach to other types of haptic data reduction schemes in terms of their effects on haptic feedback quality and teleoperator force control.

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