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# Haptic Data Reduction for Time-delayed Teleoperation Using the Time Domain Passivity Approach

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***Abstract*— We propose a perceptual haptic data reduction approach for teleoperation systems which use the time domain passivity approach (TDPA) as their control architecture for dealing with time-varying communication delay. Our goal is to reduce the packet rate over the communication network while preserving system stability in the presence of time-varying and unknown delays. Compared to the existing wave variable-based (WV-based) haptic data reduction approaches, our proposed scheme leads to smaller distortion in the force signals and robustly deals with time-varying delays. Experiments show that our proposed approach can reduce the average packet rate by up to 80%, without introducing significant distortion. In addition, the proposed approach outperforms the existing WV-based approaches in both packet rate reduction and subjective preference for the tested communication delays.**

## I. INTRODUCTION

A bilateral teleoperation system with haptic feedback (referred to as teleoperation system in this paper), allows human users to interact with a remote environment by means of slave and master devices, which exchange force and position/velocity information over a communication link [1]. The slave system is typically controlled by position/velocity commands, while the visual and haptic information sensed by the slave system during teleoperation are sent back to the master system for display (Fig. 1).

Haptic signals on both the master and slave sides are typically sampled at a rate of 1 kHz. The samples are packetized and transmitted immediately with a rate of 1 kHz. This avoids the introduction of additional processing delay which is crucial for system stability and transparency [2], [3]. The resulting high packet rate (1000 packet/s) together with the packet header overhead lead to inefficient communication in a packet-switched network [4]. To reduce the high packet rate on the network, haptic data reduction approaches that exploit the limitations of human haptic perception have been introduced in [4-7]. In these previous studies, *which we refer to as perceptual deadband (DB) coding approaches*, the communication delay was assumed to be negligible.

For teleoperation in remote environments, communication delay is a critical factor for system stability [8]. To enable stable teleoperation in the presence of significant communication delay, passivity-based control architectures, such as the wave-variable (WV) transformation (or WV architecture) [9], [10], the time domain passivity approach (TDPA) [11], [12], and other architectures [13], [14], have been developed. The WV architecture ensures system stability for arbitrarily large and constant delays. The TDPA, on the other hand, is able to deal with time-varying delay. System passivity is guaranteed by using passivity observers and passivity controllers (see Sec. II-A for more details).

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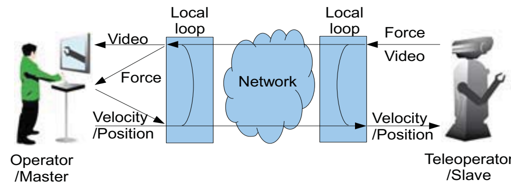


Fig. 1. Overview of a teleoperation system (adopted from [1]).

Haptic data reduction approaches for time-delayed teleoperation systems have been proposed in [15], [16], in which the wave-variable transformation is combined with the perceptual deadband (DB) approach from [4], [5]. In the remainder of this paper, we denote these methods as the WV-based haptic data reduction approaches, or short the WV-based approaches. The authors of [15] apply the DB approach directly on the wave variables and find the subjectively best deadband parameter. In [16], the authors use a method called *local computation of wave variables (LCWV)* to enable the use of the DB approach in the time domain (i.e. directly on the force and velocity signals), for known communication delay. The authors of [16] also show that their method outperforms the one proposed in [15]. Both approaches, however, can only deal with constant delay, with the assumption of known delay in [16] and without this assumption in [15]. To the best of our knowledge, there is no study on haptic data reduction for teleoperation systems with time-varying delay.

The WV architecture has been extended for time-varying delays in [17]. However, the change rate of the delay must be known, as it is one of the parameters for computing the passivity condition. This requires online parameter estimation on the communication network. Considering potential packet loss in the network and the irregular packet transmission obtained when using the DB approach for data reduction, a precise online estimation becomes challenging. For these reasons, a simpler and more flexible system structure for haptic data reduction in delayed teleoperation is required.

In this paper, we present a novel TDPA-based haptic data reduction approach (TDPA-based approach) which is able to deal with unknown and time-varying delay. Compared to the existing WV-based approaches, our proposed scheme leads to smaller distortion in the force signals and flexibly and robustly deals with time-varying communication delays. Experimental results show that the proposed TDPA-based approach outperforms the WV-based approach [16] in terms of both packet rate reduction and subjective preference for the tested communication delay of 100 $ms$.

## II. Background

### A. Time domain passivity approach (TDPA) for bilateral teleoperation control with communication delay

TDPA ensures the stability of teleoperation systems in the presence of arbitrary communication delays using passivity observers (PO) and passivity controllers (PC). The stability arguments are based on the passivity concept, which characterizes the energy exchange over a two-port network and provides a sufficient condition for the input/output stability. The TDPA architecture is able to deal with time-varying delays and packet loss without knowing the transmission parameters. In this work, we use the TDPA architecture to guarantee system stability.

*1)* **Passivity of a two-port network:** Data communication in a teleoperation system can be represented by a typical two-port network as illustrated in Fig. 2. The passivity condition for a two-port network requires a positive net energy output, which means that $E_{in}(k) \geq E_{out}(k)$ must hold at any sampling instant $k$ (system initial energy is assumed to be zero). With the assumption that the sampling rate on the velocity and force signal is substantially faster than the dynamics of the system, input and output energy flows on both the master and slave sides in [11] are separated to be $E^m_{in}(k)$, $E^m_{out}(k)$, $E^s_{in}(k)$ and $E^s_{out}(k)$. The computation of all the energy flows proceeds as follows:

$$E^m_{in}(k) = \begin{cases} E^m_{in}(k-1) + \Delta E^m(k), & \text{if } \Delta E^m(k) > 0 \\ E^m_{in}(k-1), & \text{else} \end{cases} \tag{1}$$

$$E^m_{out}(k) = \begin{cases} E^m_{out}(k-1) - \Delta E^m(k), & \text{if } \Delta E^m(k) < 0 \\ E^m_{out}(k-1), & \text{else} \end{cases} \tag{2}$$

$$E^s_{in}(k) = \begin{cases} E^s_{in}(k-1) + \Delta E^s(k), & \text{if } \Delta E^s(k) > 0 \\ E^s_{in}(k-1), & \text{else} \end{cases} \tag{3}$$

$$E^s_{out}(k) = \begin{cases} E^s_{out}(k-1) - \Delta E^s(k), & \text{if } \Delta E^s(k) < 0 \\ E^s_{out}(k-1), & \text{else} \end{cases} \tag{4}$$

where $\Delta E^m(k) = v_m(k)f_m(k)\Delta T$ and $\Delta E^m(k) = v_s(k)f_s(k)\Delta T$ are the energy changes on the master and slave sides during the $k^{th}$ sampling period. $\Delta T$ is the sampling time. $f_m$ and $v_m$ denote the force and velocity signal on the master side, and $f_s$ and $v_s$ are the force and velocity signal on the slave side.

According to (1)-(4), all energy flows on both the master and slave sides are positive and monotonically increasing. The passivity condition for the two-port network is [11]:

$$E^m_{in}(k) + E^s_{in}(k) \geq E^m_{out}(k) + E^s_{out}(k), \qquad \forall k \geq 0 \tag{5}$$

A sufficient and more conservative condition is [11]:

$$E^m_{in}(k) \geq E^s_{out}(k), \text{ and } \quad E^s_{in}(k) \geq E^m_{out}(k) \tag{6}$$

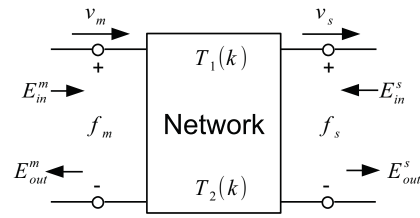


Fig. 2. Energy flow of a teleoperation system represented by a two-port network. The energy on the left (master) and right (slave) sides are further separated into input and output flows [11], [22]. $T_1(k)$ and $T_2(k)$ denote the forward and backward communication delays at sampling instant $k$.

Note that $E^m_{in}(k)$ and $E^m_{out}(k)$ are computed on the master side, and $E^s_{in}(k)$ and $E^s_{out}$ are computed on the slave side. In order to examine the system passivity according to (6), $E^m_{in}(k)$ must be sent to the slave side, and $E^s_{in}(k)$ must be sent to the master side. Due to the communication delay, the received $E^m_{in}$ on the slave side and the received $E^s_{in}$ on the master side at the sampling instant $k$ are $E^m_{in}(k-T_1(k))$ and $E^s_{in}(k-T_2(k))$, where $T_1(k)$ and $T_2(k)$ denote the forward and backward communication delays at sampling instant $k$. Thanks to the monotonic increase of the input/output energy, it is sufficient to satisfy (7) in order to satisfy (6). Thus, (7) is the general and sufficient condition for system passivity of a two-port network with communication delays [11].

$$\begin{aligned} E^m_{in}(k-T_1(k)) \geq E^s_{out}(k) \\ E^s_{in}(k-T_2(k)) \geq E^m_{out}(k) \end{aligned} \tag{7}$$

*2)* **Time domain passivity approach:** As illustrated in Fig. 3, the POs compute the input and output energy on both the master and slave sides. Meanwhile, they examine the passivity condition according to the locally computed output energy and the received input energy from the other side. If the passivity condition is satisfied, the received velocity or force signal is directly applied. If not, the PC is activated and the adaptive dampers $\alpha$ and $\beta$ are computed to dissipate the output energy and thus to preserve the system passivity.

Considering the energy dissipation ($E^m_{PC}$ and $E^s_{PC}$) due to the damping $\alpha$ and $\beta$ on the master and slave sides, the general passivity condition described in (7) should be modified. The final passivity conditions based on Fig. 3 are given as [11]:

$$\begin{aligned} W_m(k) = E^s_{in}(k-T_2(k)) - E^m_{out}(k) + E^m_{PC}(k-1) \geq 0 \\ W_s(k) = E^m_{in}(k-T_1(k)) - E^s_{out}(k) + E^s_{PC}(k-1) \geq 0 \end{aligned} \tag{8}$$

The computation of the damping $\alpha$ and $\beta$ as suggested in [11] are given as:

$$\alpha(k) = \begin{cases} 0, & \text{if } W^m > 0 \\ -\frac{W^m(k)}{\Delta T v^2_{mc}(k)}, & \text{eles, if} |v_{mc}(k)| > 0 \end{cases} \tag{9}$$

$$\beta(k) = \begin{cases} 0, & \text{if } W^s > 0 \\ -\frac{W^s(k)}{\Delta T f^2_s(k)}, & \text{eles, if} |f_s(k)| > 0 \end{cases} \tag{10}$$

In Fig. 3, the virtual mass and spring model is employed as a passive low-pass filter for the velocity and force signals. See [11] for more detail.

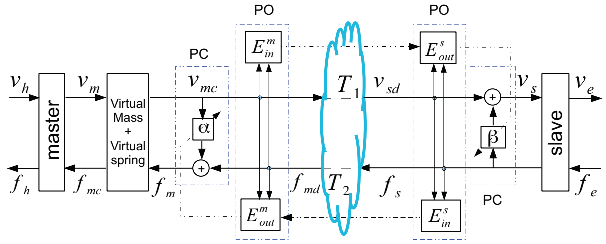


Fig. 3. A time-delayed teleoperation system with the TDPA and the virtual mass-spring filter (adopted from [11]).

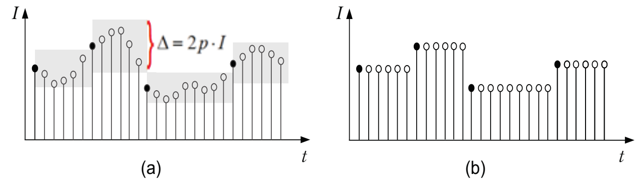


Fig. 4. 1-DoF deadband approach. The input signal (a) is irregularly downsampled and only the values represented with black filled circles are transmitted. In (b), the output signal is upsampled using the zero-order-hold method.

### B. Perceptual deadband-based haptic data reduction

Recent haptic data compression algorithms exploit the characteristics and limitations of the human haptic perception system [4-7]. These approaches are inspired by Weber's law [18], [19], which provides a mathematical model of human perception. It states that the minimum change in intensity ($\Delta I$) perceivable between two stimuli, called just noticeable difference (JND), is a constant proportion of the starting intensity of a reference stimulus $I$ [19]: $\Delta I/I = \epsilon$. The JND (or difference threshold) is identified by psychophysical methods and the ratio $\epsilon$ is called the Weber Fraction (WF) [19]. For haptic perception, the WF has been found to be in the range of $5\%$ to $15\%$, depending on the type of stimulus (force/velocity) and the limb/joint where it is applied [20].

Inspired by Weber's law, small changes in the rendered force feedback signal are considered to be unperceivable. For a given force sample $I$, the deadband parameter (DBP) $p$ defines a deadband (DB) zone $\Delta = 2pI$ (see Fig. 4). Samples that lie in the deadband zone are dropped. When the difference between the recently sent sample and the current signal value violates the deadband zone, the current value is transmitted. At the receiver side, a basic upsampling method called zero-order hold (ZOH) strategy is used to interpolate the irregularly received signal samples to a high sampling rate that is required for the local control loop.

Fig. 4 shows the principle of the DB approach. Filled circles represent the transmitted update samples. The gray zones illustrate the deadband (perception thresholds) defined by the DBP. The samples inside the zone are interpolated by the ZOH approach at the receiver side. The size of the applied deadband is proportional to the magnitude of the most recently transmitted haptic sample and the DBP $p$. If a new signal value falls outside the deadband zone, a packet is sent over the network and the current deadband zone is updated with this recent sample.

Note that the original ZOH is a non-passive reconstruction scheme [15], [16], which could jeopardize the system stability. To ensure a stable deadband reconstruction, the authors in [15], [16] have proposed a passive ZOH reconstruction strategy by modifying the original ZOH scheme. For example, in [16] the passive ZOH scheme for the force is:

$$f(k) = f(k^*) - sign(v_s)\Delta_f \tag{11}$$

where $k^* < k$ is the time instant of the most recently received signal, $f(k^*)$ is the most recently received force signal and $p$ is the deadband parameter. $\Delta_f = p \cdot f(k^*)$ denotes the DB zone with regard to the most recently received signal $f(k^*)$.

## III. TDPA-based Haptic data reduction

In this section, we present the combination of the haptic data reduction approach discussed above with the TDPA control architecture described in Sec. II-A. The deadband approach with the original ZOH method as proposed in [5] is employed for data reduction and reconstruction. As illustrated in Fig. 5, the blocks "deadband control", on both the master and slave sides, control the transmission rate of the velocity, force, and energy signals based on the DB approach discussed in Sec. II-B. At each sampling instant, if no update is received, the block "deadband reconstruction" generates the same signal as the most recently received one (original ZOH reconstruction scheme) for the subsequent computation. Compared to the original TDPA architecture, the computation of the energy in the POs (Fig. 5) for the proposed approach is modified. The energy changes on both the master and slave sides at each time instant $k$ can be described as follows:

$$\Delta E^m(k) = \begin{cases} v_{mc}(k) f_{md}^{recv}(k)\Delta T, & \text{if signal received} \\ v_{mc}(k) f_{md}(k^*)\Delta T, & \text{else} \end{cases} \tag{12}$$

$$\Delta E^s(k) = \begin{cases} v_{sd}^{recv}(k) f_s(k)\Delta T, & \text{if signal received} \\ v_{sd}(k^*) f_s(k)\Delta T, & \text{else} \end{cases} \tag{13}$$

where $k^* < k$ is the time instant of the most recently received signal update. $v_{sd}(k^*)$ and $f_{md}(k^*)$ are the most recently received velocity and force signals. $v_{sd}^{recv}(k)$ and $f_{md}^{recv}(k)$ denote the currently received velocity and force signal, respectively. Based on the signs of the energy change, the input or output energy on both the master and slave sides can be computed according to (1)-(4).

Although the original ZOH reconstruction scheme is non-passive, the POs and PCs ensure the passivity of the two-port network (marked by the blue dotted lines in Fig. 5) at each sampling instant. Thus, the original ZOH method can be directly applied without any modification. The WV-based approaches do not have such a passivity guarantee when the original ZOH reconstruction scheme is applied. Therefore, passive ZOH reconstruction strategies are necessary.

Compared to the original ZOH reconstruction method, the passive ZOH reconstruction strategies ([15], [16]), however, could lead to greater signal error between the real and the reconstructed signal and to greater signal jumps when a

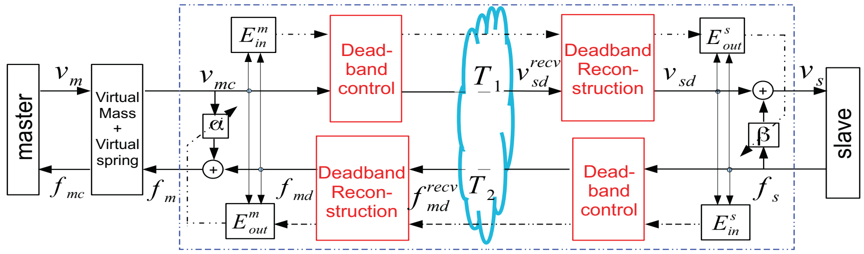


Fig. 5. Overview of the TDPA-based haptic data reduction approach.

TABLE I

COMPARISON OF DIFFERENT DEADBAND RECONSTRUCTION METHODS.

| | comm. delay | max. error | max. jump |
|---|---|---|---|
| Method in [15] | constant | $\Delta$ | $> \Delta$ |
| Method in [16] | known & constant | $\Delta$ | $> \Delta$ |
| Proposed method | unknown & time-varying | $\Delta/2$ | $> \Delta/2$ |

new signal update is received. Fig. 6(a) shows an example input signal sequence in which the two black filled circles denote the transmitted signal. The reconstructed signal using the original ZOH method is shown in Fig. 6(b), where the maximum signal error is about half the DB zone ($\Delta/2$) and the maximum signal jump is also about $\Delta/2$. Fig. 6(c) shows the reconstructed signal using the passive ZOH reconstruction strategy, where, in the worst case, the maximum signal error is $\Delta$ and the maximum signal jump is also about $\Delta$. This greater signal error/jump due to the modification of the deadband reconstruction strategy could result in additional force distortion and perceivable vibration (e.g. step effects in the force signals).

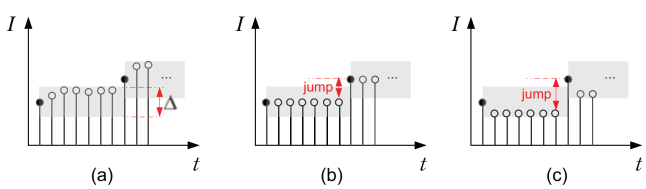


Fig. 6. Worst case example for the data reconstruction using different deadband reconstruction schemes. (a) Transmitted signal. (b) Reconstructed signal using the original ZOH strategy. (c) Reconstructed signal using the passive ZOH strategy proposed in [15], [16]. The Y-axis denotes the signal intensity, either in the time domain or in the wave-variable domain.

Note that an alternative structure of the proposed combination is to monitor the energy after the deadband control / reconstruction. In this case, the passive ZOH scheme needs to be adopted to guarantee the passivity of the whole system. The structure with passive ZOH, however, could lead to larger force distortion (step effects) compared to the one with original ZOH as shown in Fig. 6.

In general, the advantages of our proposed TDPA-based haptic data reduction approach compared to the WV-based approaches are the flexibility to deal with time-varying communication delays and the lower distortion in the force signal. Tab. I contrasts these approaches.

## IV. EXPERIMENTAL EVALUATION

The desired low packet rate and the targeted high system transparency are conflicting objectives in teleoperation system design. Considering the limits of human haptic perception, however, slight distortions introduced by the deadband approach are not necessarily perceivable. With a proper DBP, a low packet rate and a high perceptual transparency can be achieved simultaneously.

We conduct subjective tests to evaluate the performance of the proposed TDPA-based haptic data reduction approach in the presence of communication delays. In addition, the resulting average packet rate as well as the user preference of our approach are compared with those of the WV-based haptic data reduction approach proposed in [16].

The experiments are conducted in a virtual environment (VE) with a real haptic device (Geomagic Touch®) as illustrated in Fig. 7. The VE is developed based on the Chai3D library (www.chai3d.org). A 1-DoF rigid wall with a stiffness of 700N/m is placed in the middle of the VE as the remote object on the slave side. The dynamics of the virtual robot in the VE are designed based on the dynamics of the haptic device [21].

### A. Experiment I: Performance of the TDPA-based approach

The first experiment is conducted to verify the feasibility of the proposed TDPA-based haptic data reduction approach for constant and varying communication delays.

**1) Setup and procedure.** The round-trip delay (RTT) of a typical internet communication is normally from zero to hundreds milliseconds. Three different RTTs are tested in this experiment: 1) 10 $ms$ constant delay, 2) 100 $ms$ constant delay, and 3) varying delay with a mean delay of 100 $ms$ and a Gaussian distributed jitter with a standard deviation

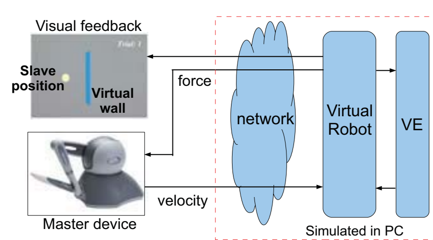


Fig. 7. Experimental setup. The communication network, the virtual robot, and the VE are simulated in a PC using the CHAI3D library.

TABLE II

RATING SCHEME USED IN EXPERIMENT I.

| Rating level | Description |
|---|---|
| 5 | no difference |
| 4 | perceptible difference (step effects or other disturbing) |
| 3 | slightly different, disturbing |
| 2 | different and strongly disturbing |
| 1 | completely different and distorted |

of 30 $ms$. The selection of these delay values is motivated by RTT measurements from Germany to the east coast of the US where we have observed a mean delay of 95 $ms$. Furthermore, we want our results to be comparable to the related work in [15], [16], where similar delay values were chosen. For each tested delay scenario, a series of DBP values are tested: 0%, 2%, 5%, 8%, 10%, and 15%. A DBP of 0% corresponds to the performance of the original (without the deadband approach) TDPA architecture.

Note that although the deadband approach reduces the packet rate, it also leads to step-effects in the haptic signal (see Fig. 4). The main purpose of this experiment is to investigate the effect of the DBP on the subjective quality of the haptic signals compared to the case when no compression is used. Thus, the subjects need to give a rating for each DBP by comparing the perceived similarity of the haptic interaction between the case of using the given DBP value and the case of using a reference (see Tab. II). The reference (the same delay as the current trial with 0% DBP, designated level 5), is considered as the "best" performance of the original (uncompressed) TDPA architecture for a tested delay. The reference can be selected at any time during the experiment.

During the experiment, the DBPs are randomly arranged. The subjects need to interact with the virtual wall by pressing on the surface and slowly vary the applied force with a frequency of about 0.5Hz. This constraint in motion corresponds to the assumption of low frequency inputs for the passivity condition as discussed in Sec. II-A, which is also used in the experiment in [11]. Moreover, position drifts introduced by the TDPA are compensated after each trial when the virtual robot is in free space.

Fifteen subjects participated in the experiment, ranging in age from 25-45. The whole experiment is repeated twice for each subject. A headset with active noise cancellation is worn to isolate the subjects from ambient noise.

**2) Results.** The packet rate vs. the deadband parameter (DBP) for the three tested communication delay settings

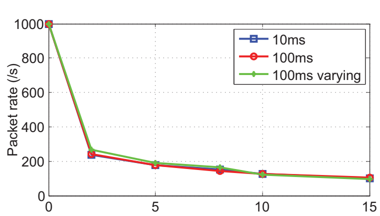


Fig. 8. Packet rate vs. deadband parameters for different delays.

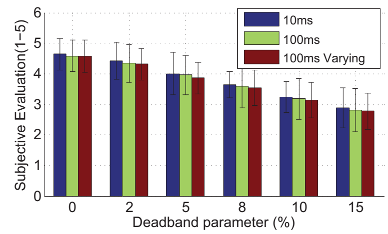


Fig. 9. Mean and standard deviation of the subjective ratings vs. DBP.

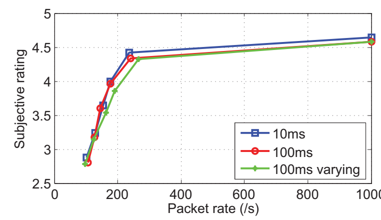


Fig. 10. Subjective quality vs. packet rate (QR-curve).

are shown in Fig. 8. As expected, higher DBPs lead to lower packet rate. Obviously, the DBP has a dominant effect on the packet rate. On the other hand, the tested communication delays influence the damping of the passivity controller, which leads to modified velocity and force values. The modified velocity and force signals in turn affect the packet rate. Thus, the communication delays have an indirect influence on the packet rate. However, the packet rate curves for the three tested communication delays are very close to each other in Fig. 8, which indicates that the aforementioned indirect effect is small for the tested delays.

The subjective rating vs. the DBP is shown in Fig. 9. Similar to Fig. 8, higher DBPs lead to lower subjective ratings, since the subjects perceive larger difference (step effects in the force signal) with increasing DBPs compared to the reference. Please note that the ratings with the same DBP for different delays are not directly comparable, since we use different references for different delays. But all the references in each delay case are designated as rating level 5. For each delay, the subjects need to only rate the similarity of the haptic interaction between the reference (DBP=0) and the case with DBP>0. The high similarity of the subjective rating for the three tested delays (ANOVA on communication delays for all six DBPs: $p_{1\sim 6} > 0.71$) implies that the distortion in the force signal caused by the deadband approach is independent of the tested communication delays.

The combined curves from Fig. 8 and Fig. 9 are shown in Fig. 10, which illustrates the relationship between the subjective quality and the packet rate (also called QR-curve). If a DBP of 5% is applied, the packet rate can be reduced by up to 80%, while the subjective quality remains sufficiently high (at about level 4). Hence, the TDPA-based haptic data reduction approach achieves a high packet rate reduction without introducing significant distortion (mainly the step effects). Moreover, as we use different references for different delays, the three curves in Fig. 10 are not directly comparable. From the high similarity of the three curves we can only conclude that the tested delays have limited (insignificant) influence on the packet rate and subjective quality. Whether this observation also holds for delays larger than 100 $ms$ will be investigated in our future work.

### *B. Experiment II: TDPA-based vs. WV-based haptic data reduction*

Compared to the WV-based haptic data reduction approaches, a notable advantage of using the proposed TDPA-based approach is the ability to deal with time-varying delays. In this experiment, we compare the performance of our proposed TDPA-based method with the WV-based haptic data reduction approach proposed in [16] in terms of packet rate reduction and subjective preference. According to the discussion in Sec. III, high frequency vibrations introduced by the passive ZOH reconstruction scheme result in perceivable force distortion. In addition, vibrations in the force signal also lead to quick force changes and, thus, result in a larger packet rate. Based on this discussion, our hypothesis is: *the packet rate for the TDPA-based approach is smaller than for the WV-based approach if the DBP is chosen to be the same. Meanwhile, the TDPA-based approach is preferred by the subjects compared to the WV-based approach.*

In order to simplify the comparison of the quality between the TDPA-based and WV-based approaches for the subjects, we adopt an indirect comparison by introducing a common reference for the two approaches. In the common reference, the applied DBP value is the same as in the other two approaches, but the delay is set to be zero and passivity control is not applied. The common reference is considered to have standard environment impedance with respect to the applied DBP. The comparisons are thus made between the common reference and the TDPA-based approach, as well as between the common reference and the WV-based approach. The force signal in the common reference is distorted only by the DB approach. In the presence of delay, the DB approach has to be combined with the TDPA or WV control architectures to ensure system stability. These control architectures introduce additional distortions. In this experiment, we want to find out which combination (TDPA+DB or WV+DB) performs better for the tested scenarios.

**1) Setup and procedure.** The tested DBP values are the same as those in the first experiment. The same subjects as in the first experiment participated in the second experiment. Since the WV-based approach is not able to deal with varying delays, we set the round-trip communication delay in this experiment for both control architectures to be 100 $ms$ and constant. The experiment has six trials for the six randomly ordered DBPs. In each trial, subjects need to compare the two approaches (TDPA-based and WV-based) with the common reference during their interaction with the virtual wall. After each trial, the subjects had to answer the following two questions: 1) which approach shows a more similar behavior to the common reference? 2) which approach do you prefer?

**2) Results.** The resulting packet rate vs. DBP curves are illustrated in Fig. 11. A significantly lower packet rate can be observed for our proposed TDPA-based haptic data reduction approach (pairwise T-test on packet rate: $p < 0.005$ for DBPs 5%-15%). For a DBP of 5%, the mean packet rate of the WV-based approach is about 260 packets/s, while the packet rate of the proposed TDPA-based approach is about 180 packets/s. This corresponds to an improvement of more than 30% in packet rate reduction.

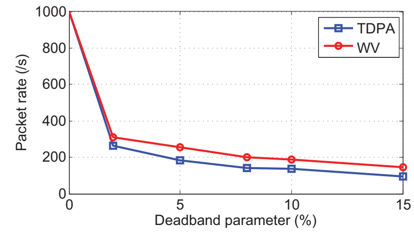


Fig. 11. Comparison of packet rate reduction for two haptic data reduction approaches in delayed teleoperation systems.

TABLE III

RESULTS OF THE FIRST QUESTIONNAIRE: SUBJECTIVE IMPEDANCE.

| Question 1: impedance similarity | | | | | | |
|---|---|---|---|---|---|---|
| DP (%) | 0 | 2 | 5 | 8 | 10 | 15 |
| TDPA-based | 73% | 80% | 73% | 80% | 93% | 100% |
| WV-based | 27% | 20% | 27% | 20% | 7% | 0% |
| **Question 2: preference** | | | | | | |
| DP (%) | 0 | 2 | 5 | 8 | 10 | 15 |
| TDPA-based | 73% | 87% | 80% | 80% | 93% | 93% |
| WV-based | 27% | 13% | 20% | 20% | 7% | 7% |

The results of the two questionnaires are shown in Tab. III. For all the tested DBPs, most of the subjects responded that the TDPA-based approach shows a more similar behavior to the common reference. The similarity according to the subjects is mainly in the environment stiffness. Most subjects suggest that though the TDPA-based approach introduces irregular distortions (occasionally quick force changes, see Sec. V-A), the WV-based approach shows a significantly softer environment than the TDPA-based approach. According to the answers to the second question, the TDPA-based approach is also preferred by the subjects compared to the WV-based one. Note that the results of the similarity and preference evaluations are very similar to each other, which implies that most of the subjects prefer the TDPA-based approach which introduces smaller modifications of the environmental impedance (stiffness). The hypothesis postulated at the beginning of Sec. IV-B could hence be confirmed.

## V. DISCUSSION

### *A. Limitations*

Although the TDPA-based haptic data reduction approach shows its ability to deal with time-varying delays and a better performance compared to the WV-based approach, the experiments conducted in this paper have limitations.

Due to the limited range of the tested communication delays in our experiments, general conclusions on the efficiency of packet rate reduction and the quality of subjective experience for the proposed approach are difficult to obtain. This is mainly because the distortion in the force signals introduced by the TDPA control architecture changes for different communication delays. According to [11] and our experimental results, the TDPA architecture introduces irregular force jumps (strong force changes). These force jumps happen when the adaptive damping is quickly changed by the passivity controller to dissipate the system energy. The behavior of the force jumps, e.g. the strength of the jumps and the duration of the jumps, however, varies for different communication delays even for similar motion [11]. The influence of different communication delay and such distortion in the force signals on the performance of the DB approach as well as the subjective quality is still unknown. This will be investigated in our future work.

### *B. DB-based packet reduction vs. packet loss*

In the DB-based haptic data reduction approach, if the change between the most recently sent haptic sample and the current sample is sufficiently small, the current sample is not sent (dropped). This can also be interpreted as a packet loss. According to [11], packet loss introduces additional artifacts in the force signal, since the master and slave cannot exchange the energy information and, thus, the passivity controller behavior becomes more conservative. Larger DBP values lead to higher packet rate reduction and, thus, result in higher "packet loss" rates and greater distortions. The difference between the "packet loss" behavior and the real packet loss is that in the former case the signal sender knows when the communication stops and when it recovers. Based on this knowledge, it is possible to design an energy predictor to enable less conservative control for the passivity controller.

### *C. TDPA vs. WV control architecture*

A performance comparison between the TDPA and WV control architectures is not the goal of this paper. However, the observation from the experiment II for a DBP value of 0% implies that the TDPA architecture causes less modification on the environment impedance (stiffness), which shows an advantage of using the TDPA architecture. A similar observation can be also found in [11]. In the WV architecture, although the displayed impedance can be increased to be closer to the original environment impedance by increasing the characteristic impedance $b$, free space motion requires a very small value of $b$ [15]. Typically, a compromise is made. In our experiment, we set $b = 3.5\ Ns/m$.

## VI. CONCLUSIONS

In this paper, we present a control scheme that combines the TDPA architecture with the perceptual deadband-based haptic data reduction approach. Our approach allows for a reduction of the haptic data using the original ZOH deadband reconstruction approach, while preserving system stability in the presence of time-varying (unknown) communication delays. The proposed approach can reduce the packet rate by up to 80%, without introducing significant distortion for the tested communication delays of up to $100\ ms \pm 30\ ms$. Compared to the WV-based approach, the proposed system is subjectively more transparent. In addition, the proposed approach has a higher efficiency in packet rate reduction for the tested communication delay.

Future work will focus on the system performance for different delays in a real network and teleoperation setup. In addition, the energy predictor mentioned in Sec. V-B can be developed to enable a less conservative passivity control.

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