Perceptual Haptic Data Reduction in Telepresence and Teleaction Systems

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1. Introduction

Vision and hearing play a significant role in the perception of our surroundings. This fact has aptly justified and reinforced our inclination of focusing research in man-machine interaction traditionally on these modalities. Inspired by the recent progress in human-machine interaction, robotics, augmented reality, contemporary scientists and engineers are concentrating efforts towards seamlessly integrating the haptic modality with the well established ones of audio and video. This realization is rapidly gaining the field of haptics (from the Greek *haptikos*, pertaining to the sense of touch), the attention that it has rightfully deserved.

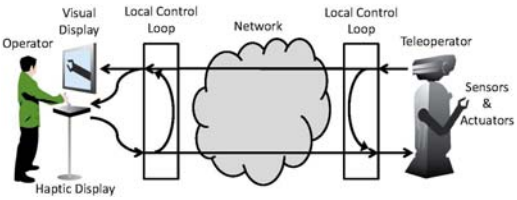

Figure 1: Schematic overview of a visual-haptic telepresence and telemanipulation system (adapted from [1]).

In particular, typical telepresence and teleaction (TPTA) systems rely on haptics. In these systems a human operator controls a remote teleoperator through a human system interface device. As soon as the teleoperator encounters contact with its surroundings, corresponding feedback is transmitted to be displayed to the human operator. The communication system therefore closes a global control loop. In this way, the TPTA system enables the perception of objects including physical manipulation as well sensing their material properties. An overview of a TPTA system is illustrated in Fig. 1.

Communication unreliabilities, such as time delay and packet loss, can jeopardize the system's stability resulting in dangerous unbounded oscillations of the devices. Besides that, reduction of the transmitted haptic data requires proper reconstruction on the receiver side to guarantee a stable system.

For reasons of stability, haptic data samples are typically transmitted immediately upon generation on a 1 packet/sample basis for packet-based networks like the Internet. This leads to a packet being triggered for transmission at every millisecond (corresponding to the stringently required haptic update rates of 1 kHz). Essentially, too many packets are generated too fast with relatively less worth of information conveyed. Previous studies have established the fact that such high packet-rates are difficult to maintain over general-purpose networks like the Internet [2]. A good haptic compression/data reduction scheme should solve this predicament.

2. Perceptual coding of haptic signals

Perceptual deadband coding (PDC) schemes are developed to cope with these challenges [3]. The PDC approach exploits the limitations of human haptic perception for lossy data reduction. It is summarized by a simple mathematical relationship between the physical intensity of a haptic stimulus and its phenomenologically perceived intensity (known as the Weber's law). When trying to perceive the difference between physical quantities (e.g. weights) in succession, it is not the difference itself that makes an impression upon us, rather the ratio of this difference to the magnitude of the first quantity. This ratio is constant and is denoted by *k*, a percentile value. We translate this observation that Weber made to our field of interest, namely perceptual haptic data reduction. By defining perceptual thresholds – the so called deadband – we can distinguish perceivable changes from unperceivable changes in haptic signals. By transmitting only those haptic samples which lead to a perceivable change, we can significantly decrease the packet rate on the network without impairing the user experience. The samples skipped from transmission are approximated at the other side by simple interpolation schemes like the "hold last sample"-approach or via linear prediction. The size of such a deadband is controlled by the parameter k. The greater the k value is, the larger the deadband and hence the applied perceptual thresholds. Substantial average haptic data reduction ratios of up to 85-90% of the otherwise bulky data are obtained using this approach.

3. Multiple-Degree-of-Freedom Extension

Real-world TPTA systems deploy typically more than one degree-of-freedom (DoF). In order to enable perceptual data reduction in multi-DoF TPTA scenarios, [4] proposes the construction of an isotropic deadzone. In two dimensions, the deadzone can be described by a circular; in three dimensions by a spherical region which is centered at the tip of the currently applied haptic sample vectors. Furthermore, its radius is defined to be a fraction of the haptic sample magnitude. However, when extending the haptic data reduction schemes from a single-DoF to multi-DoFs, the spatial orientation of haptic sample vectors acts as an additional perceptual domain. Therefore, its influence on haptic perception thresholds is to be investigated. In this context, psychophysical experiments in [5] reveal that haptic force feedback perception is a function of the spatial orientation of the force feedback itself. In order to adopt the perceptual deadband scheme to these findings, [6] proposes the construction of a novel deadzone shape that takes the form of a frustum of a cone. In this way, the perceptual data reduction approach can reflect the dependencies of the spatial direction of force feedback onto the perceptual thresholds which allows for a significant improvement in data reduction performance.

4. Control Issues

Several control architectures have been proposed to enable stable TPTA sessions in the presence of communication unreliabilities. To guarantee stability when there is an arbitrarily large constant time delay in the network the scattering transformation is proposed in [7]. Instead of the power conjugated variables, i.e. force and velocity, a linear combination of them is transmitted. The time-varying delay and packet loss challenge are addressed in [8] and [9] respectively.

By requiring each subsystem of the TPTA system to dissipate energy, and therefore be more conservative, stability can be guaranteed. Using the same rationale for the data reconstruction strategies of a haptic data reduction algorithm, stability is shown for the PDC in [10]. For robotic systems with more than one degree-of-freedom, the corresponding data reduction algorithm and an optimization-based reconstruction strategy are presented in [11].

The selected control architecture determines apart from stability, the robustness and transparency of the TPTA system. A detailed discussion exceeds the scope of this article and the reader is referred to the survey article [12].

5. Error-Resilient Haptic Data Reduction

Internet-based TPTA are subject to packet delays, jitter and packet losses. Particularly, when packet losses occur in haptic communication while using the PDC scheme in combination with predictive coding, several artifacts can be observed on the reconstructed signal such as bouncing, increased roughness and a “glue effect” [13].

Due to strict delay constraints traditional packet loss compensation strategies such as retransmissions based on time-outs are not feasible for haptic communication. Therefore, in order to achieve error-resilient haptic data reduction, [13] proposes the construction of a Markov tree [14] that enables the estimation of the most likely state of the receiver. This allows us to adaptively add redundancy to the haptic channel if the estimated state at the receiver significantly deviates from the desired signal trajectory and if this deviation becomes perceivable. Combined with the state-of-the-art haptic data reduction approaches we can achieve perceptual error-resilient haptic communication.

6. Conclusion and Future Work

With recent advances in haptic technology, the efficient communication of haptic signals is gaining relevance. Integrating more degrees-of-freedom leads to an increased amount of data and strict delay constraints result in high update packet rates in the network. We address this challenge by deploying a mathematical model of human perception for multiple degrees-of-freedom which allows the reduction of the packet rate by up to 90%. Moreover, the stability issues due to packet losses and delays have been successfully addressed from a control engineering perspective. An error-resilient perceptual coding for networked haptic interaction has been developed allowing the haptic communication to operate seamlessly while operating in the presence of adverse communication channel conditions.

Future work will address the extension of the model of the human haptic perception by integrating additional findings from psychophysics, such as multimodal dependencies and dynamic perception thresholds. A comprehensive psychophysical model furthermore enables the development of novel methods for objective quality evaluation. The complexity of the error-resilient haptic communication approach is also to be decreased and its efficiency further improved.

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