Applications of Machine Learning in Haptic Perception

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Haptic data transmission has been a recent area of interest in the haptics research community for the past few years. Unlike video and audio transmission, the haptic data transmission is bidirectional in nature. It forms a global control loop over a communication network. In order to maintain the stability of the control loop, only a small amount of communication delay (1-5 ms) is permitted, which is smaller compared to the permissible limit required for typical applications involving audio and video. Therefore, only a small number of samples can be incorporated in a packet, which leads to a high packet rate. The high packet rate may cause network congestion over existing network protocols like Internet, causing loss of the packets and instability of the global control loop. Thus, it is required to reduce the packet rate while maintaining the quality of the perception. In recent past, many researchers have used perceptually adaptive sampling scheme based on the Weber's law for the purpose. According to Weber's law, a force signal will be perceived as being a different one from the reference signal if its relative difference with respect to the reference force exceeds a certain threshold value. This threshold is named as the Weber threshold or the just noticeable difference (JND). Hence, in case of perceptually adaptive sampling, a kinesthetic force signal will be sampled at points where the relative difference exceeds the JND. It means that this approach transmits only perceptually significant sample points, and the JND determines their perceptual significance. Hence, it is required to study and identify different adaptive sampling strategies for haptic signals.

We first seek to identify good adaptive sampling strategies for haptic signals.Our approach relies on experiments wherein we record the response of several users to haptic stimuli. We then learn different classifiers to predict the user response based on a variety of causal signal features. The classifiers that have good prediction accuracy serve as possible candidates to be used in adaptive sampling. We compare the resultant adaptive samplers based on their rate-distortion tradeoff using synthetic as well as natural data. For our experiments, we use a haptic device with a maximum force level of 3 N and have a subject base of 10 users. Each user is subjected to several piecewise constant haptic signals and is required to click a button whenever he/she perceives a change in the signal. For classification, we use classifiers based on level crossings and Weber's law, and also random forests using a variety of causal signal features. The random forest typically yields the best prediction accuracy and a study of the importance of variables suggests that the level crossings and Weber's classifier features are the most dominant. The classifiers based on level crossings and Weber's law have good accuracy (more than 90%) and are only marginally inferior to random forests. The level crossings classifier consistently outperforms the one based on Weber's law even though the difference is small. Given their simple parametricform, the level crossings and Weber's law based classifiers are good candidates to be used for adaptive sampling. We study their rate-distortion performance and find that the level crossing sampler is superior. For example, for haptic signals obtained while exploring various rendered objects, for an average sampling rate of 10 samples per second, the level crossings adaptive sampler has a mean square signal reconstruction error about 3 dB less than the Weber sampler.

In the next study, we extend this work to 2-D kinesthetic haptic signals, and study the possible structures of perceptual dead zones (which separates out perceptually significant and insignificant data), defined for the adaptive sampling schemes. In order to achieve this, we generate 2D piecewise constant haptic force signals. The haptic response is recorded extensively for 8 different users. The recorded data has two labels: perceived or non-perceived. We use several classifiers to predict the label of the haptic response. Our thesis isthat a classifier which predicts better can possibly offer a good structure of the dead zone. We again study the Weber, level crossing and general purpose classifiers for the purpose. We find that the level crossing classifier gives a significant improvement over the Weber classifier. The level crossings classifier assumes a circular dead zone around the reference vector, and the radius of the deadzone is independent of the magnitude of the reference vector. In order to study the directional sensitivity of the haptic perception, we modify the standard level crossing classifier to have a general shape as defined by a conic section and estimate the parameters of this conic section, the result of which demonstrates that kinesthetic perception is indeed circularly symmetric, and is independent of direction. Hence, a user does not have directional preference while perceiving the change in 2-D haptic force.

In the previous studies on perceptually adaptive sampling, it is not investigated how the just noticeable difference for the kinesthetic force stimulus is affected by the rate of temporal change of the stimulus. The perceptual limitations of a human being are not fully exploitedby the fixed JND. For example, if the signal changes very slowly, it is difficult for a user to react to the change, and when the change is too quick, the user may not respond because of the human response time (minimum time required for reacting to achange). Thus, the fixed JND will contribute inessential packets for such kind of signals. Hence, in this work, we attempt to examine the relationship between the JND and the rate of change of the force stimulus. For this purpose, we design an experiment where a user is exposed to a linearly increasing/decreasing haptic force stimulus, and is asked to react to the change. We intend to find a decision boundary between the perceived and non-perceived points. The separation boundary defines a relationship between the JND and the rate of change of the force stimulus. We apply machine learning techniques to design classifiers on the recorded data to estimate the best fit decision boundary. Both parametric and non-parametric classifiers are used for the purpose. Our results show that the JND decreases for a faster change in the force stimuli. We also exhibit that there is an asymmetric behavior of perception between the increasing and the decreasing force stimuli. Hence, the findings of the work have a feasible relevance in better design of a haptic data compression algorithm.

Finally, we estimate the temporal resolution of a user - the minimum time spacing required in perceiving two consecutive jumps in a kinesthetic force stimulus. In a teleoperation, perceptually significant force samples are transmitted from a robot to a human operator. If the time spacing between two consecutive, perceptually sampled kinesthetic force stimuli is less than the minimum time spacing (temporal resolution) required in perceiving the jump discontinuity, then the second force stimulus will not be perceived even if it is well above the just noticeable difference. Hence, there is no need to transmit the second force sample to the operator. As a matter of fact the teleoperator needs to slow down the operation. Thus, for the transmission in a teleoperation, the temporal resolution needs also to be considered while effecting perceptually adaptive sampling. In this work, we propose a statistical method to estimate the temporal resolution. In order to achieve this, we design an appropriate experimental set up, and record the haptic responses for several users extensively. We show that the temporal resolution lies between 20-30 ms for most users. We also study the effect of perceptual fatigue on the temporal resolution, and validate all results using the classical psychometric approach.
The details of these methods will be discussed in the lecture.

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