Department of Electrical and Computer Engineering
University of Rochester, Rochester, NY
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Hidden Markov Models for Supercapacitor State-of-Charge Tracking and Audio Watermarking

Andrew Nadeau

Supervised by
Professor Gaurav Sharma

Abstract

This thesis examines applications of the hidden Markov model (HMM) in two very different settings.

The HMM is first applied to estimate the available stored energy in a supercapacitor. The main benefits of supercapacitor energy storage over electrochemical batteries are high instantaneous power and ability to survive 100 to 1000 times as many charge-discharge cycles as a battery. We focus on an additional benefit, a more direct relation between a supercapacitor's terminal voltage and stored energy, to improve energy awareness. However, a simple capacitive approximation cannot adequately represent the stored energy in a super- capacitor. It is shown that the three-branch equivalent circuit model provides more accurate energy awareness. This equivalent circuit uses three capacitances and associated resistances to represent the supercapacitor's internal SOC (state-of-charge). However, the SOC cannot be determined from one observation of the terminal voltage, and must be tracked over time using inexact measurements. We present: 1) a Kalman filtering solution for tracking the SOC (which is equivalent to an HMM); 2) an on-line system identification procedure to efficiently estimate the equivalent circuit's parameters; and 3) experimental validation of both parameter estimation and SOC tracking for 5F, 10F, 50F, and 350F supercapacitors. Validation is done within the operating range of a solar powered application and the associated power variability due to energy harvesting. The proposed techniques are benchmarked against the simple capacitive model and prior parameter estimation techniques, and provide a 67% reduction in root-mean-square error for predicting usable buffered energy.

In a second completely different setting, HMMs are applied to watermark synchronization. We propose an audio watermark designed for operation over analog playback channels where detection must be robust to both noise and desynchronization. Desynchro- nization results from small differences in the playback and recording rates. In addition to addressing robustness, the proposed watermark also provides computationally efficient detection. Computational efficiency relies on a frequency domain, magnitude-only embed- ding strategy that reduces the resolution of the cross-correlations calculated at the detector. For robust blind detection (does not access the original signal) we propose a dynamic time warping (DTW) based detection procedure. Results demonstrate that the proposed watermark survives analog playback and warping up to ±2%. Additionally, compared with a recent baseline scheme that uses brute force resampling to search for resynchronization, the proposed watermark is 300 times more computationally efficient, and does not compromise robustness to either desynchronization (e. g. jitter, resampling, time warping, frequency scaling) or non-desynchronizing modifications (e.g. AAC compression, additive noise).

Finally, we incorporate data embedding via convolutional encoding in an extension of the DTW based watermark. Decoding uses a HMM with a joint state for both alignment and error correction. For the previous watermark without a data payload (zero-bit watermarking), DTW is constrained to find an alignment sequence between the audio signal and watermark sequence that monotonically progresses through the two signals. Decoding the joint state modifies the Bahl-Cocke-Jelinek-Raviv (BCJR) decoder to allow the DTW alignment sequence to follow a trellis defined by the convolutional code. As opposed to performing alignment and BCJR decoding sequentially, a common HMM framework for both allows a true joint implementation. There is no loss of information before applying error correction and the estimated alignment utilizes the redundancy of the encoded water- marksignal to correct alignment errors. Using a cyclic redundancy check (CRC) and outer concatenated block code, the proposed watermark survives analog playback with consumer hardware (*Vizio* soundbar and *Motorola* smartphone) at a data rate of 5.4 bits per second (bps) (inner code), 0.6 bps (outer code with CRC). Additionally, watermark embedding maintains the perceptual quality of the host audio content.