A Modified Baum–Welch Algorithm for Hidden Markov Models with Multiple Observation Spaces

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Abstract—In this paper, we derive an algorithm similar to the well-known Baum–Welch algorithm for estimating the parameters of a hidden Markov model (HMM). The new algorithm allows the observation PDF of each state to be defined and estimated using a different feature set. We show that estimating parameters in this manner is equivalent to maximizing the likelihood function for the standard parameterization of the HMM defined on the input data space. The processor becomes optimal if the state-dependent feature sets are sufficient statistics to distinguish each state individually from a common state.

Index Terms—Baum–Welch algorithm, class-specific, EM algorithm, expectation-maximization, Gaussian mixtures, hidden Markov model (HMM), parameter estimation, sufficient statistics.

I. INTRODUCTION

THE class-specific method was recently developed as a method of dimensionality reduction in classification [1], [2]. Unlike other methods of dimension reduction, it is based on sufficient statistics and results in no *theoretical* loss of performance. Performance is always lost going from theory to practice due to (1) loss of information when reducing data to features, and (2) approximation of the theoretical feature PDFs. There is always a tradeoff between the desire to retain as much information as possible (by increasing the feature dimension) and the desire to obtain better PDF estimates (by decreasing the dimension). The class-specific method obtains a better compromise by allowing more information to be kept for a given maximum feature dimension. It does this by assigning a separate feature set to each class. Now we extend the idea further to the problem of HMM modeling when each state of the HMM may have its own approximate sufficient statistic.

II. MATHEMATICAL RESULTS

We show in this section that the class-specific HMM is merely a different way to parameterize the likelihood function of the conventional HMM. Let $L(\mathbf{X}; \lambda)$ be the likelihood function defined for the input data $\mathbf{X}$. A special class-specific likelihood function, $L^s(\mathbf{Z}; \lambda^s)$ is defined using the class-specific (state-specific) statistics $\mathbf{Z}$. It is shown below that maximizing $L^s(\mathbf{Z}; \lambda^s)$ over λ^s is equivalent to maximizing $L(\mathbf{X}; \lambda)$ over λ with special constraints. While it is not necessary for $\mathbf{Z}$ to be sufficient for this to be true, the processor

constructed from class-specific sufficient statistics will be optimal, provided there is no PDF estimation error.

A. Standard Parameterization and Notation

We consider a set of state occurrences $\boldsymbol{\theta} \triangleq \{q_1 \ldots q_T\}$ where $1 \leq q_t \leq N$. The sequence $\boldsymbol{\theta}$ is a realization of the Markov chain with state priors $\{\pi_j, j = 1, 2 \ldots N\}$ and $N \times N$ state transition matrix $A = \{a_{ij}\}$. Rather than observing the states $\boldsymbol{\theta}$ directly, we observe the stochastic outputs $\mathbf{X} \triangleq \{\mathbf{x}_1, \mathbf{x}_2 \ldots \mathbf{x}_T\}$ which are realizations from a set of state PDFs

$$p_j(\mathbf{x}) \triangleq p(\mathbf{x}|H_j), \quad j = 1, 2 \ldots N$$

where H_j is the condition that state j is true. We assume the observations are independent, thus

$$p(\mathbf{X}|\boldsymbol{\theta}) = \prod_{t=1}^{T} p_{q_t}(\mathbf{x}_t).$$

The complete set of parameters defining the HMM are

$$\lambda \triangleq [\{\pi_j\}, \{a_{ij}\}, \{p_j(\cdot)\}]$$

where $\sum_{j=1}^{N} \pi_j = 1$, $\sum_{j=1}^{N} a_{ij} = 1$. The likelihood function is the joint density of the observation sequence given the model parameters and is written (see [3, Eq. 17])

$$
\begin{aligned}
L(\mathbf{X}; \lambda) \triangleq p(\mathbf{X}; \lambda) &= \sum_{\boldsymbol{\theta}} p(\mathbf{x}, \boldsymbol{\theta}; \lambda) \\
&= \sum_{\boldsymbol{\theta}} \pi_{q_1} p_{q_1}(\mathbf{x}_1; \lambda) \prod_{t=2}^{T} a_{q_{t-1} q_t} p_{q_t}(\mathbf{x}_t; \lambda)
\end{aligned}
$$

(1)

where $\sum_{\boldsymbol{\theta}}$ is a summation over all possible state sequences of length T. The maximum likelihood (ML) estimate of λ is defined as

$$\hat{\lambda} \triangleq \arg\max_{\lambda} L(\mathbf{X}; \lambda). \tag{2}$$

We use notation similar to Rabiner [3] with the exception that we represent state PDFs as $p_j(\cdot)$, and observations as $\mathbf{x}_t$. In the paper, functions beginning with the letters "b" and "p," always denote PDFs. The letter "b" is reserved for components of mixture PDFs and "p" is used for all other PDFs. The exception is any function carrying the superscript "s" which is *not* a PDF.

Hidden Markov Models Baum Welch Algorithm

F Rizvi

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