Bayesian Subspace Hidden Markov Model for Acoustic Unit Discovery

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Abstract

This work tackles the problem of learning a set of language specific acoustic units from unlabeled speech recordings given a set of labeled recordings from other languages. Our approach may be described by the following two steps procedure: first the model learns the notion of acoustic units from the labelled data and then the model uses its knowledge to find new acoustic units on the target language. We implement this process with the Bayesian Subspace Hidden Markov Model (SHMM), a model akin to the Subspace Gaussian Mixture Model (SGMM) where each low dimensional embedding represents an acoustic unit rather than just a HMM’s state. The subspace is trained on 3 languages from the GlobalPhone corpus (German, Polish and Spanish) and the AUs are discovered on the TIMIT corpus. Results, measured in equivalent Phone Error Rate, show that this approach significantly outperforms previous HMM based acoustic units discovery systems and compares favorably with the Variational Auto Encoder-HMM.

Index Terms: Bayesian Inference, Hidden Markov Model, Subspace Model, Variational Bayes, Low-resource languages, Acoustic Unit Discovery

1. Introduction

State-of-the-art Automatic Speech Recognition (ASR) systems rely upon very large amount of speech recordings paired with a textual transcriptions. While this approach has proven to be very successful it is however limited to the very few languages having enough resources to train an ASR system. Due to the cost of data collection and transcription, broadening the range of speech technologies to any language remains an unreachable objective. Parallel to the mainstream ASR, there has been a growing interest in the paradigm of unsupervised learning of speech [1]. Unsupervised speech learning attempt to use machine learning techniques to extract various information (phonetic content, speaker identity, ...) from unlabeled recordings. While this is considerably harder than standard ASR, solving this problem would have a considerable impact on the field by reducing the amount of human labour necessary to build a full fledged ASR pipeline. It is also important to emphasize that the linguistic diversity is diminishing worldwide. Many languages are now considered endangered and risk to disappear in a near future. Affordable speech technologies could be a precious tool to help linguist and communities to document and preserve these languages.

This work focuses on the specific task of acoustic unit discovery (AUD). Given a collection of unlabeled recordings in a specific language the task is to learn a set of basic speech units (also called pseudo-phones) to describe the language. AUD algorithms have to solve 3 problems: to segment the speech, to cluster the segments into units and to infer how many units are necessary to describe the language. Several approaches have been proposed relying upon Bayesian non-parametric version of the Hidden Markov Model (HMM) [2][3][4]. An important recent extension of this model is the VAE-HMM [5][6][7] which combines the traditional HMM with Variational Auto Encoder [8]. However, most of the AUD algorithms are prone to model speaker/channel or any non-phonetic variability. To address this issue we propose the Bayesian Subspace HMM (SHMM). The SHMM is a HMM based AUD model in which the parameters of each unit is constrained to be in the phonetic subspace of the total parameter space. This restriction forces the AUD model to focus on the phonetic content of the speech signal and to ignore irrelevant information.

2. Model

2.1. Standard Acoustic Unit Discovery

Let \( X = \{x_1, \ldots, x_N\} \) be the sequence of \( N \) observed speech frames, \( U = \{u_1, \ldots, u_P\} \) a set of \( P \) acoustic units, \( v = \{v_1, \ldots, v_N\}, v_i \in U \) a sequence of variable indicating to which unit each speech frame is associated with and \( Z = \{z_1, \ldots, z_N\} \) some model dependent latent variables. We consider generative models for which the complete likelihood of the data factorizes as:

\[
p(X, Z|v) = \prod_{n=1}^{N} p(x_n, z_n|v_n)
\]

and the likelihood of a speech frame for a given unit is member of the exponential family of distribution:

\[
p(x_n, z_n|v_n = u) = \exp \left\{ \eta_u^T T(x_n, z_n) - A(\eta_u) \right\}
\]

where \( \eta_u \in \mathcal{H} \) is the \( D \)-dimensional vector of natural parameters of one acoustic unit, \( T(x_n, z_n) \) are the sufficient statistics and \( A(\eta_u) \) is the (log-)normalization constant of the density. Note that the nature of the model for the units (HMM, GMM, Linear Dynamical Model, ...) will depend on the value of \( z_n \) and the sufficient statistics \( T \). In this work we consider that each unit is modeled by a HMM with a GMM for each state’s emission but it can be replaced by any model satisfying Eq. [1] and Eq. [2]. Previous works [2][3][4] use special cases of this model to perform the AUD. More precisely, one can understand AUD as finding a set of vectors \( \eta_1, \ldots, \eta_P \) such that the likelihood of the observation is maximized.[1] This search is difficult because speech recordings encode many factors other than the phonetic information (speaker identity, emotions, environment, ...) and the AUD algorithm may maximize the likelihood while modeling non-phonetic information.

2.2. Subspace HMM

To avoid the AUD model to capture non-phonetic information we proposed the Subspace HMM (SHMM) which constrains

\[\text{These algorithm also learn the number of acoustic units } P \text{ needed to fit the data}\]
the acoustic units parameters to live in the phonetic space. This
model extend the unsupervised HMM by assuring that the pho-
etic information of a language is contained in a subspace of the
total parameters space. Formally, it is defined as:

\[ \eta_u = f(W^T h_u + b) \quad (3) \]

where \( f : \mathbb{R}^D \rightarrow \mathcal{H} \) is a differentiable function. We further
refine this subspace model by introducing a prior over the sub-
space’s parameters:

\[
W_{r,c} \sim \mathcal{N}(0, \sigma_{W_{r,c}}^2) \quad (4) \\
b \sim \mathcal{N}(0, I) \quad (5) \\
h_u \sim \mathcal{N}(0, I) \quad (6)
\]

As depicted in Fig. 1a, the bases of \( W \) span the subspace con-
taining the phonetic variability. Since the parameters of the
acoustic units are constraint to live in a (small dimensional)
subspace, the AUD algorithm is cast to the problem of finding
the set of embedding \( h_{u_1}, \ldots, h_{u_N} \) which maximizes the like-
lihood of the observations. By constraining the search in the
phonetic subspace we therefore force the algorithm to ignore
non-phonetic source of variability.

Note that Subspace Gaussian Mixture Model [9], Joint Fac-
tor Analysis [10], Subspace Multinomial Model [11], etc. are
special cases of Eq. (3). In fact, Eq. (3) is the general form of
any subspace model for which the complete likelihood is the
member the exponential family of distribution. We denote Eq.
(3) as the Generalized Subspace Model (GSM) of which the Sub-
space HMM, like other models aforementioned, is just a spe-
cial instance. The graphical representation of the (GSM) is de-
picted in Fig. 1a. To complete our definition of the SHMM
we need to specify the mapping \( f \) from \( \mathbb{R}^D \) to the natural pa-
ters space \( \mathcal{H} \). In our settings each unit is modeled by a
HMM with a 3 states left-to-right topology and each state has
a GMM emissions with \( K \) Gaussian components with diag-
onal covariance matrix. For convenience we introduce the vector
\( \psi = W^T h + b \) which can be decomposed into 3 parts
\( \psi = (\psi_1, \psi_2, \psi_3)^T \). \( \psi_i \) is the vector parameters (before the
mapping \( f \)) associated with the ith HMM state. \( \psi_i \) further de-
composed into \( \psi_i = (\psi_{i}^{r}, \psi_{i}^{μ}, \psi_{i}^{K,Σ}) \), where \( \psi_{i}^{r} \) is the vector encoding the parameters of the mix-
ture’s weights and \( \psi_{i}^{μ}, \psi_{i}^{Σ} \) are the vector of encoding the
parameters of the mean and covariance matrix of the jth Gauss-
ian component respectively. We set \( f \) such that:

\[
\pi_{i,j} = \frac{\exp(\psi_{i,j}^{σ})}{1 + \sum_{k=1}^{K-1} \exp(\psi_{i,k}^{σ})} \quad (7) \\
\mu_{i,j} = \psi_{i,j}^{μ} \quad (8) \\
\Sigma_{i,j} = \text{diag}(\exp(\psi_{i,j}^{Σ})) \quad (9)
\]

where \( \exp \) is the element wise exponential function. One could
also include the transition probabilities of the HMM but we kept
them as fixed parameters in this work.

2.3. Estimating the phonetic subspace

Unlike previous AUD algorithms, our model requires to spec-
ify the phonetic subspace (parameterized by \( W \) and \( b \)) before
searching the acoustic units. This is a “chicken or egg” prob-
lem since we need the phonetic subspace to find the pseudo-
phones of the language and we need to know the phones of a
language to estimate the subspace. However, this problem can
be alleviated by observing that many languages in the world
have common phones. It is reasonable to believe that the pho-
etic subspace of language is well approximated by a phonetic
subspace estimated from one or several other languages for
which we have labeled data. Interestingly, this rational natu-
ually fits the Bayesian approach of the problem of AUD. Given
unlabeled set of observation \( X^{(i)} \) in a target language, previ-
ous Bayesian AUD algorithms try to estimate the inventory of
(pseudo-)phones \( U^{(i)} \) of the target language by estimating:

\[
p(U^{(i)} | X^{(i)}) = \frac{p(X^{(i)} | U^{(i)}) p(U^{(i)})}{p(X^{(i)})} \quad (10)
\]

If we now assume the phonetic subspace to be estimated from
the observations \( X^{(i)} \) of another language with known inven-

Figure 1: (a) Directed Acyclic Graph of a Generalized Subspace Model. Dashed lines represent deterministic relationship between
variables. SHMM, JFA, SGMM are special cases of this model. In this work each embedding \( h_u \) encodes the parameters of one HMM
corresponding to an acoustic unit. (b) Illustration of the subspace model for acoustic units. Each point of the plane corresponds to the
parameters of an acoustic unit model and the blue line represents the subspace defined by \( f(W^T h + b) \). Given an acoustic unit model
corresponding to the sound aa, moving its parameters along the subspace will change the model to represent another unit/phone (ow, z in this example).
Conversely, moving the parameters away from the phonetic subspace will push the model to capture non-phonetic information (for instance speaker gender).
The problem is intractable, so we use the Variational Bayes (VB) algorithm to approximate the posterior of the model's parameters. This approximation will lead to a two steps procedure for the SHMM AUD algorithm. First, given the labeled data of one or several languages, the prior over the acoustic units is estimated. Informally speaking, we force the model to learn “what is a phone.” Second, the unlabelled data of the target language is clustered into pseudo-phones given the phonetic knowledge acquired by the model during the first step.

2.4. Training

The two steps of the training (learning the prior and clustering the units) are carried out by optimizing the same objective function except that when estimating the prior the acoustic unit transcription of each utterance is known. The presence or absence of the transcription will be reflected in p(v). When there is no transcription, p(v) can be understood as a “pseudo-phone” loop (see 3 for details) and when the transcription is known then p(v) is just the inference graph used for forced alignment in a traditional HMM based ASR system.

Since the estimation of the exact posterior of the model’s parameters is intractable we use the Variational Bayes (VB) objective function to find an approximate posterior:

\[ L[q] = \langle \ln p(X|\Xi,\Theta) \rangle_q - D_{KL}(q(\Xi,\Theta)||p(\Xi,\Theta)) \quad (14) \]

\[ \Xi = \{Z, v\} \quad (15) \]

\[ \Theta = \{W, b, h_u, \ldots, h_u\} \quad (16) \]

where \( \langle \ldots \rangle_q \) denote the expectation w.r.t. the distribution \( q \) and \( D_{KL} \) is the Kullback-Leibler divergence. Eq. (14) is not tractable for arbitrary distribution \( q \) so we consider the restricted set of distributions with the following mean-field factorization and the given parameterization:

\[ q(\Xi,\Theta) = q(\Xi|\phi)q(\Theta|\zeta) \quad (17) \]

\[ \zeta = (m, \lambda) \quad (18) \]

\[ q(\Theta|\zeta) = N(m, \text{diag}(\exp(\lambda))) \quad (19) \]

The parameters \( \phi \) of the variational posterior over \( \Xi \) will depend on the type of the model of the acoustic unit. For the case of a HMM, this is the probability to be in a particular state given the sequence of observations. Under these restrictions the optimization reduces to:

\[ \phi^*, \zeta^* = \arg\max_{\phi, \zeta} L(\phi, \zeta) \quad (20) \]

Finally, we approximate \( \nabla_\zeta L(\phi^*, \zeta) \approx \nabla_\zeta L'(\phi^*, \zeta) \) by using the so-called re-parameterization trick introduced in [8]:

\[ \epsilon_t \sim \mathcal{N}(0, 1) \quad (23) \]

\[ \Theta_t = m + \text{diag}(\exp(\frac{\lambda}{2}))\epsilon_t \quad (24) \]

\[ L'(\phi, \zeta) \approx \frac{1}{L} \sum_{t=1}^L \ln p(X|\Xi,\Theta_t) \]

\[ -D_{KL}(q(\Xi,\Theta)||p(\Xi,\Theta)) = L'(\phi, \zeta) \quad (26) \]

In practice, we use the ADAM optimizer [13] to update \( \zeta \) and we use \( L = 10 \) samples to compute the empirical expectation.

The parameters \( \phi \) are re-estimated every 1000 updates of \( \zeta \).

3. Experiments

3.1. Data, Features and Metrics

We conducted our experiments with the TIMIT [14] database and 3 languages from the GlobalPhone corpus [15], German (GE), Polish (PO) and Spanish (SP). For each of the 3 languages of the GlobalPhone corpus we kept only 3000 randomly selected utterances. We used two sets of features: (i) the MFCC features and concatenated with their first and second derivatives (ii) the Multi-Lingual bottleNeck (MBN) features trained on 17 Babel’s languages [16]. The set of languages used to train the MBN features does not include English, German, Polish or Spanish. Both sets of features were extracted at a rate of 100 Hz. For the case the MBN features, the audio signal was down-sampled to 8kHz.

We evaluated the different AUD algorithms in terms of phonetic segmentation and equivalent Phone Error Rate (eq. PER) [17][18]. For the phonetic segmentation we used the standard Recall, Precision and F-score measured against the timing provided in the TIMIT database with the 61 different phones. We tolerated boundary shifted by + 1 frame (10 milliseconds). To compute the eq. PER, we mapped each acoustic unit to one of the 61 phones it overlaps the most with. Then, we reduced the reference transcription and proposed transcription to the 39 phone set [18] and computed the PER.

3.2. Estimating the phonetic subspace

First, we ran a controlled experiment to assess whether the SHMM is able to properly learn the phonetic subspace of a language. In this experiment we used the MBN features and each HMM state had 8 Gaussian components. First we trained a Bayesian HMM phone recognizer on the 48 phone set with a flat phonotactic language model on the traditional TIMIT training set (no SA* utterances) and decoded on the test set mapping the phones to the 39 phone set. This phone recognizer achieved 36.4% Phone Error Rate (PER). This number is very high since we have removed crucial elements of the traditional ASR pipeline (language model, context-dependent phones, ...) in order to evaluate the quality of the acoustic model. For information, the mono phone system of Kaldi gives 37.3% when having a flat phonotactic language model. We then trained a SHMM based phone recognizer with varying subspace dimension using the same training and testing setup as the baseline HMM. We used the baseline model to provide the first estimate of \( \phi \) which we modified so that all the Gaussian components within a state have equal responsibility. We pre-trained the subspace for 15000 updates before to update \( \phi \) then we re-estimated \( \phi \) after every 1000 updates of \( \zeta \) for 30 iterations. Results, shown
Table 1: Comparison of the SHMM against other AUD models in terms of phonetic segmentation (Recall, Precision, F-score) and equivalent Phone Error Rate (%).

| Model         | Features          | Prior Language | Recall | Precision | F-score | eq. PER |
|---------------|-------------------|----------------|--------|-----------|---------|---------|
| HMM [5]       | MFCC + Δ + ΔΔ    | None           | -      | -         | -       | 65.4    |
| VAE-HMM [5]   | MFCC + Δ + ΔΔ    | None           | -      | -         | -       | 58.9    |
| VAE-BHMM [6]  | MFCC + Δ + ΔΔ    | None           | 43.46  | 37.8      | 40.43   | 64.92   |
| HMM           | MFCC + Δ + ΔΔ    | None           | 43.56  | 36.91     | 39.96   | 68.25   |
| SHMM          | MFCC + Δ + ΔΔ    | GE             | 64.83  | 67.6      | 66.19   | 58.89   |
| SHMM          | MFCC + Δ + ΔΔ    | GE+PO          | 61.7   | 62.14     | 61.92   | 58.23   |
| SHMM          | MFCC + Δ + ΔΔ    | GE+PO+SP       | 62.79  | 61.93     | 62.35   | 56.91   |
| SHMM          | MBN               | GE             | 43.07  | 52.8      | 47.44   | 55.14   |
| SHMM          | MBN               | GE+PO          | 42.47  | 49.6      | 45.76   | 54.1    |
| SHMM          | MBN               | GE+PO+SP       | 43.88  | 49.29     | 46.43   | 49.2    |

Figure 2: PER of the SHMM for varying subspace dimension.

3.3. Acoustic Unit Discovery

We now consider the case of unsupervised learning of speech where English is assumed to be a low-resource language. In this setup we use the complete TIMIT set (training, development and testing set) as the corpus from which to extract acoustic units. In this experiment all the languages close to the target language would be beneficial. Even though it is possible, we didn’t update the posterior of the phonetic subspace while clustering the acoustic units. We considered all the phones of all the languages to be unique and didn’t merge them while estimating the subspace. The posterior of the embeddings \( q(h_u) \) corresponding to the German, Polish and Spanish phones were discarded before the AUD clustering.

The results are presented in Table 1 and differs significantly depending on the input features. The SHMM always benefits from learning the phonetic subspace in term of eq. PER. Interestingly, the baseline HMM fails to benefit from the MBN features as it underperforms compare to the HMM trained on MFCC features. The SHMM, thanks to its subspace, learns from other languages to fully exploit the discriminatively trained features. Regarding the segmentation evaluation, the SHMM better segments the speech compared to the simple HMM. However, we observe that using more than one language does not necessarily improves the segmentation. Also, contrary to the eq. PER, the MBN features does not seem to be ideal to get accurate segmentation.

Finally, we tried to label the TIMIT corpus with a HMM phone-recognizer (MBN features) trained on German, German and Polish and German, Polish and Spanish and we interpreted the output phones as acoustic units. For these 3 models the eq. PER was 61.22 % (GE), 66.47 % (GE+PO) and 71.96 % (GE+PO+SP). Contrary to the SHMM this naive approach does not benefit from having more languages.

4. Conclusions

We proposed a new model for AUD: The Subspace HMM. Unlike other AUD models the SHMM is trained in a supervised fashion on one or several languages to learn the notion of ”phone”. This phonetic knowledge is encoded into a nonlinear subspace of the total parameter space. Then, the SHMM searches a set of of acoustic units in this subspace which maximizes the likelihood of the observations of the target language. The SHMM outperforms the HMM based AUD and is competitive with the VAE-HMM. When using discriminatively trained features the SHMM achieves 49.2 % equivalent PER on TIMIT without any supervision on the target language.

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