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Theoretical Analysis of Hidden Markov Models: A Systematic Review

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Abstract: The basic theory and working of Hidden Markov Models have been remained supreme choice for experts of different domains for more than 80 years ago. But in the past decade it has made prominent place in the domain of Speech Processing (Speech Recognition, Speech Synthesis).

Objective: This study presents complete theoretical analysis of HMM based on systematic review method using vast comprehensive set of articles from well known researchers. Here, enormous view of HMM states, working, architectural representation, domains of HMM applicability have been discussed to explore the utility of HMM and relevance of HMM as appropriate model for Speech Recognition area. After complete study, the relevant importance of HMM has been shown and identify the need as appropriate model whether stand-alone or in conjunction with some other models for speech recognition.

Method: Extensive and Standard literature review method which includes set of articles, journals, conferences and workshops material for review process.

Results: Importance of HMM is classified on the basis of accuracy that has been achieved by different researchers. General structure of HMM and applicability of HMM has been presented. Algorithms have been mentioned which in conjunction with HMM are proved as worth to be used with.

Conclusion: Importance of HMM has been presented in the way of literature review where HMM has been utilized for greater accuracy. Such is a boon n the domain of Speech recognition and some other applications. Number of researchers have been used and many are still using for solving many of the problems, stand alone HMM or some latest variations in conjunction with other techniques have been used for attaining good results.

1. INTRODUCTION AND MOTIVATION

An HMM is a doubly stochastic process with an underlying stochastic process that is not observable (it is hidden), but can only be observed through another set of stochastic processes that produce the sequence of observed symbols [1]. Hidden Markov model, either with discrete output probability distributions or continuous output probability density functions has been proved as most powerful statistical tools for modeling speech signals. These models and their applicability in the area of speech recognition is not somewhat new. Such concept had been highlighted and published by Baum and some of his colleagues in between 1960-70, but actually this model was implemented by Baker and Jelinek at IBM in 1970s. Deep understanding and prime application of the theory of HMM in the field of speech processing has been discovered in past several years.

1.1. Inspiration for work

1. HMM is being used in different domains from last many years. Therefore, study is focusing on its history
2. State of art, showing multiple domains of HMM, so the presented research is based on extensive and systematic search and gaps have also been included for some further study.

2. REVIEW METHOD IN PAPER

Extensive and Systematic review approach which has been opted in this paper is resulting with-

2.1. Planning of review

Here some important concepts about HMM, role in noisy and clean environment, algorithms of HMM have been discussed

2.2. Sources of information

Abundant of data sources are necessary to conduct extensive and broad literature review. Before doing so, appropriate databases are required to select to increase the relevance of paper.

1. IEEE
2. Elsevier
3. Springer

2.2.1. Some Additional sources of information

1. Reference lists from primary studies and other review articles.
2. Various Books with concerned topics

3. ELEMENTS OF AN HMM

HMM is comprised of three basic elements:

1. There are N numbers of states in the HMM. Although they are hidden, but for some important applications states and sets pose relevant significance. In the experiments of coin tossing, each and every state corresponded to a distinct biased coin. All states in HMM are connected with each other in such a way that each state can be traversed and accessible from any other state(s). Each state as $S = \{S_1, . . . S_N\}$, and the state at time t as q_r are included here.
2. There are M, numbers of different observed symbols in each state which are supposed to have correspondence with the physical outcome of intended system which is under consideration. Example- In coin tossing experiments, the observation symbols could be either heads or tails; Here, symbol $V = \{v_1, v_2, \ldots v_M)$ used as independent symbol.
3. The state transition probability distribution $A = \{aij\}$ where,

$$a_{ij} = P[q_{t+1} = S_t \mid q_t = S_i],$$
$$1 \leq i,$$
$$j \leq N$$

4. The observation symbol probability distribution in state j, $B = \{b_j(k)\}$, where

$$b_i(k) = P[V_k \text{ at } t \mid q_t = S_i],$$
$$1 \leq j \leq N$$
$$1 \leq k \leq M$$

5. The initial state distribution $\pi = \{\pi_j\}$ where

$$\Pi_i = P[q_1 = S_i],$$
$$1 \leq i \leq N$$

As HMM model, consider a system with organized set consisting of N different states, $S_1, S_{2,} \ldots, S_N$. at every evenly spaced discrete time, the system continuously has to experience a change of state as per the set of probabilities which are having association with the state.

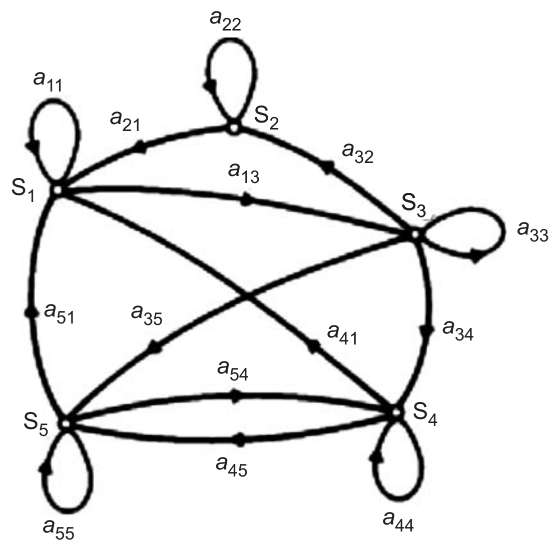

Figure 1: A Markov chain with 5 states (labeled S_1 to S_5) with selected state transitions [3]

The above presented stochastic process is an observable Markov model. Here, output of the process has been described as set of states at every instant of time and state are correspondingly physical or observable. For more description, let us take 3-state Hidden Markov Model example regarding weather. For this, there is an assertion that once a day, the weather is observed with one of the possible states, say-

State #1: Rain

State #2: Cloudy

State #3: Sunny.

The matrix A of state transition probabilities is shown as-

$$A = \{a_{ij}\} = \begin{bmatrix} 0.4 & 0.3 & 0.3 \\ 0.2 & 0.6 & 0.2 \\ 0.1 & 0.1 & 0.8 \end{bmatrix}.$$

3.1. The Three Basic Problems with HMM

As per the study of HMM which is done in earlier section, there are three significant problems which are need to combat for making the HMM applicable for real-world applications. Problems of HMM can be described as following:

1. **Problem 1:** For an observed sequence O for a given model, say λ with (A, B, π) elements, how coherent computation of Pr (O | λ) can b done? It is the probability of observed sequence in given model.
2. **Problem 2:** For an observed sequence O, how to choose corresponding state sequence, say Q which is highly optimal in some of the ways (which can be explained as best for observations)?
3. **Problem 3:** How to adjust the model parameters, say A = (A, B, λ) to maximize the P(O | λ)?

4. LITERATURE REVIEW

HMM in Speech Recognition has gained much of attention due to its accuracy results. This stochastic process has been used by many of the researchers since from its origin. How different researchers have used and what their results were with HMM, is next part of study.

JAY G. WILPON et. Al, have worked for connected word recognition based upon HMM. In this development, extraneous noise and background remained challenging. System correctly recognized with 99.3% of purely isolated speech and 95.1% fluent speech.

Mathew A. Siegler and Richard M. Stern (1995) have used HMM state Transition Method to correct the errors due to fast delivery of speech. 4% - 6% accuracy had been remained with this approach

Yuval Cohen et. Al (1997) with aid of HMM based algorithm worked for speech recognition with some additive noise.

Mark Gales and Steve Young (2008) carried out research work to present the core architecture of HMM based LVCSR. In this work they had considered news broadcasting to explore the work.

Stefan Widmann and Reinhold Haeb-Umbach (2009) in their work had used a new hybrid technique of SLDM models with HMM for feature enhancement. Along with use of HMM, SLDM modeling technique had proved very beneficial for the aim of improving accuracy.

Zeliang Zhang, Xiongfei Li (2011) had also studied the HMM modeling technique to derive algorithms for lip reading recognition. In their work they had used 10 words which had been identified by modified HMM algorithm. Accuracy remained 78.7% from 71.4% by improved HMM algorithm

Kuldeep Kumar and R.K. Aggarwal (2011) by using HMM (HTK) developed Hindi Speech Recognizer. System was for 30 Isolated Words and 8 different speakers for training process. Accuracy remained 94.63% for system

Preeti Saini et. Al (2013) had worked for Hindi speech recognition. On the basis of HMM (HTK) recognizer has been developed, accuracy remained 96.61 and 95.49% with 10 states in HMM. System was trained for 113 Hindi words.

Wiqas Ghai and Navdeep Singh (2013) carried out their research for Punjabi Speech recognition. HMM based recognizer was able to recognize continuous speech recognition. Nine Speakers were invited for recording. 100 sentences of Punjabi Language designed. Sentence Level accuracy remained 80-87%.

Feisal Dani Rahman et. Al (2014) developed Malay Speaking system with small database. For this system, HMM model has been used with which 76% accuracy has been achieved.

Asadullah et. Al (2016) developed Urdu Based Speech Recognition system where HMM has been used for 250 isolated Urdu words. 10 speakers have trained the system and results were 62.0% - 87.2%.

Colin Champion, S.M. Houghton(2016) in their paper use Cs-HMM technique, and the problem they had addressed was to recover sequence of phonetic units. Here, model was outlined for sonorant speech.

Table 1
Table for Different level of accuracies achieved by different researchers using HMM

S. No.	*Researcher(s)*	*Title of Paper*	*Accuracy achieved*
1.	Kai-Fu Lee, Hsiao-Wuen Hon, Mei-Yuh Hwang	The Sphinx Speech Recognition System [17]	96%
2.	C.N Lee, L.R Rabiner, R Pieraccini, J.G Wilpon	Acoustic modeling for large vocabulary speech recognition [18]	57.7% and 91.6%
3.	D. Giuliani, M. Matassoni, M. Omologo, P. Svaizer	Training of HMM with Filtered Speech Material For Hands Free Recognition [19]	94.9% - 98.7%
4.	Wei HSN, Cheong-Fat CHAN, Chiu-Sing CHOY, Kong-Pang PUN	An Efficient MFCC Extraction Method in Speech Recognition [20]	94.43%
5.	Zeliang Zhang, Xiongfei Li	A Study on Improved Hidden Markov Models and Applications to Speech Recognition [21]	78.7%
6.	Ms. Vimala, Dr. V. Radha	Speaker Independent Isolated Speech Recognition System for Tamil Language using HMM [9]	88%
7.	Kuldeep Kumar and R.K. Aggarwal	Hindi Speech Recognition system using HTK[10]	94.63%
8.	Preeti Saini, Parneet Kaur and Mohit Dua	Hindi Automatic Speech Recognition Using HTK [24]	96.61%
9.	Feisal Dani Rahman, Noraini Mohamed, Mumtaz Begum Mustafa, Siti Salwah Salim	Automatic Speech Recognition System for Malay speaking Children [25]	76%
10.	Asadullah, Arslan Shaukat, Hazrat Ali, Usman Akram	Automatic Urdu Speech Recognition Using Hidden Markov Model [26]	62.0%-87.2%

5. ALGORITHMS DEVELOPED IN HMM

Different researchers have devised different algorithms to work under the base of HMM. Depending upon application domain HMM remained dominant Modeling technique. These models are widely being used in areas of science and engineering (many more – (Machine Learning-Human Computer Interaction, Speech learning, Economics and Finance). Technically it is a finite state model or machine which consists of number of hidden states with possible output observations with some of the transition probabilities, and probably with output and initial state probabilities with **Q, O, A, B and** π symbols respectively. Different algorithms have been devised in HMM as per the different problems that are to be deal with. Mainly there are three problems (canonical) which can be solved by HMM by designing three algorithms. These can be discussed as-

1. With given parameters of model, calculate the particular output sequence probability, which can be done with the aid of ***Forward and Backward algorithms*** of HMM
2. With given parameters of model, observe the sequence of hidden states for generating given output sequence and can be can be solved by ***Viterbi algorithm***.
3. With given output sequence, observe the set of state transitions and output probabilities which can be handled by ***Baum-Welch algorithm***

5.1. Baum Welch Algorithm in HMM

The Baum-Welch algorithm comprises of computing two functions, *i.e.*, Forward and Backward probabilities *i.e.*, $\alpha(i, t)$ and $\beta(i, t)$, for each state i and each frame t for any given (O) observation sequence. Here, for each observation Forward and Backward functions calculate the weight. In other words, this algorithm is used to determine hidden parameters in HMM. Leonard E. Baum and Lloyd R. Welch have introduced this algorithm.

For O (O_1…..O_t) distinct observation sequences which are explicitly available for HMM, the procedure that is used is Baum-Welch reestimation. It automatically estimates the parameters of Hidden Markov Model via forward-backward algorithm. Here,Forward and Backward probabilities are to be calculated at fist stage for the observation sequence. Later on, various involvements are acquired, which in turn, yields distinct computational complexity for discrete and continuous HMM, which involves three different parameters (R, C, M) for acoustic representations, discrete output distributions, Gaussian components in output distributions respectively.

5.2. Boosting Algorithm with HMM

Boosting method, the prevailing algorithm improves the accuracy of learning algorithm. This technique efficiently trains and combines the collection and makes much more focus on misclassified examples. For this, ***AdaBoost*** algorithm probability distribution is introduced. It is a recently proposed algorithm which generates composite classifier with sequential trained classifiers by focusing on some certain patterns. Initially, there exists same weight for every training example and for subsequent iterations; and increased values of weights of misclassified examples. Using calculated weights after being trained, a distinguish classifier is trained. Same process is repeated, until set of individual or base classifiers are achieved. The prime motive behind application of AdaBoost in speech recognition is its capability in training and on error generalization. This is for “matched and mismatched conditions”, to the training data. Carsten Meyer and Hauke Schramm in their paper discussed about boosting algorithms which they have applied to Speech recognizers (HMM-based) but at utterance level. In the area of speech recognition, boosting algorithm has yielded significant improvements for test errors from standard maximum likelihood training. Authors have also extended such algorithm for LVSCR. Another variation in AdaBoost algorithm is AdaBoost.M2 algorithm, which is the most popular variant for multiclass ranking loss problems. AdaBoost.M2 also referred as AdaBoost.

6. HMM AS SIGNIFICANT MULTI LINGUISTIC SPEECH RECOGNITION TOOL

HMM has become most commonly used tool for speech recognition (speaker dependent and speaker independent), which has made machine capable to respond to human speech which in turns, act as commands given to it. Briefly, three steps are needed to be implemented by HMM for such process. Preprocessing, Feature Extraction and Classification on the basis of speech command recognition. There is also one more important fact about HMM, it is not language bounded. Speech recognition is being supported by many languages and HMM is working as powerful platform for making such recognition possible for multiple languages worldwide. Either for isolated words, connected or for continuous speech, HMM is acting as base source.

In this paper, we have also discussed that HMM is reliable and useful tool for multiple language speech recognition purpose. Malayalam, Hindi, Punjabi, Tamil, Bangla, Arabic, Assamese, Kannada are some of the Indian languages with which HMM as speech recognition tool has yielded good accuracy rate. Combination of HMM with some of the latest prevailing techniques is also in trend for researchers to work with for significant results in speech recognition process. Hidden Markov Model with different languages-

Table 2

S.No.	*Authors*	*Language*	*Title of Paper*	*Accuracy Rate*
1.	Yang Xiaocui , Sun Lihua	English	English Speech Recognition System Based on HMM in Matlab [27]	96%
2.	Preeti Saini, Parneet Kaur, Mohit Dua	Hindi	Hindi Automatic Speech Recognition Using HTK [10]	96.61, 95.49%.
3.	Vedant Dhandhania, Jens Kofod Hansen, Shefali Jayanth Kandi, and Arvind Ramesh	Hindi**	A Robust Speaker Independent Speech Recognizer for Isolated Hindi Digits [28]	75%
4.	Ms.Vimala.C, Dr.V.Radha	Tamil	Isolated Speech Recognition System For Tamil Language Using Statistical Pattern Matching And Machine Learning Techniques [29]	97.92%
5.	MD. Abdullah-al-Mamun, Firoz Mahmud	Bangla	Performance analysis of Isolated Bangla speech recognition system using Hidden Markov Model [30]	85.714%
6.	Cini Kurian and Kannan Balakrishnan	Malayalam	Connected digit speech recognition system for Malayalam language [31]	99.5%
7.	Feisal Dani Rahman, Noraini Mohamed, Mumtaz Begum Mustafa, Siti Salwah Salim	Malayalam	Automatic speech recognition system for Malay speaking children [25]	76%
8.	Nagesha	Kannad	Continuous Speech Segmentation and Recognition: Some Novel Approaches [32]	73%
9.	Wiqas Ghai and Navdeep Singh	Punjabi	Continuous Speech Recognition for Punjabi Language [33]	82.18%

7. APPLICABILITY OF HMM IN DIFFERENT DOMAINS

HMM is a doubly stochastic process where it contains non-observable and observable sequences of system. Multiple algorithms are available in HMM with which every researcher must be familiar with. They are- Forward Algorithm / Backward Algorithm, Viterbi Decoding, Baum Welch Algorithm (Expectation Maximization), K-means clustering, and Vector Quantization etc.HMM is applicable to many fields where recovering the data sequence is prime goal. Applications of HMM include-

1. HMM in Speech Recognition
2. HMM in Cryptanalysis
3. HMM in Speech Synthesis
4. HMM in Machine Learning
5. HMM in Activity Recognition
6. HMM in Gene Prediction

1. **HMM in Speech Recognition :** Work on Speech Recognition with HMM initiated in 1980s. In 1989 *X.D. Huang and M.A. Jack* had worked for SC-HMM. In 1989 Kai-Fu Lee t.al had also worked for Sphinx Speech Recognition system where HMM had been used with VQ. Such System was large vocabulary, speaker independent and continuous system. Till today, Speech Recognition with HMM has been applied on various languages- Hindi, Punjabi, Urdu, Bangali, Assamesse, Tamil and Bangla as well.

2. **HMM in Cryptanalysis :** *Rohit Vobbilisetty et. al* have worked for Cryptanalysis using HMM. They have applied HMM for solving the substitution ciphers, and then they have determined accuracy of algorithm with function of ciphertext length and number of randomly restarts [12]

3. **HMM in Speech Synthesis :** *Heiga Zen et. al* in their paper presented 2 types of softwares. One has been developed in Dec 2002, which was open source software toolkit with the name HMM Based Speech Synthesis System (HTS). This was very effective platform for Speech.

4. **HMM in Activity Recognition :** *Hao Xu et. al* had made use of HMM in their work to classify the joints into multiple actions using HMM. 3D skeleton had been used for activity recognition and data is obtained with Kinect Sensor. DTW and Euclidean geometry distance had been used to obtain probable activities from trained data. Promising accuracy achieved with such combination [15].

5. **HMM in Gene Prediction**, *Xutao Deng and Hesham Ali* in their project, developed a Gene Function, which was basically a tool for prediction and HMM based. They made use of double-split Hidden Markov Model with 3-fold cross-validation and it yielded 51% accuracy [16].

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