DYNAMIC TIME WARPING (DTW) ALGORITHM IN SPEECH: A REVIEW

Munshi Yadav[1], M. Afshar Alam[2]
[1]*Dept. of CSE, Guru Tegh Bahadur Institute of Technology, New Delhi*
[2]*Dept. of CSE, School of Engineering Sciences & Technology, Jamia Hamdard, New Delhi*

Abstract: This paper explores the study of dynamic time warping (DTW) algorithm, which is very much used in speech processing and other pattern matching applications. Study has been carried out for deferent types of dynamic time warping algorithm like sparse DTW, fast DTW, derivative DTW, iterative DTW, quantized DTW, qualitative DTW, iterative deepening DTW etc, and their use. The dynamic time warping algorithms and advanced dynamic time warping algorithms have been analysed keeping in view the various performance parameters.

Keyword: *Dynamic time warping, advanced dynamic time warping, pattern matching, speech recognition, Multi-stage DTW etc.*

I. INTRODUCTION

Dynamic time warping (DTW) algorithm is based on dynamic programming, problem solving approach and used for measuring similarity between two sequences, which may vary in time or space. Similarity is measured by computing a distance between two time series. Like any algorithm based on dynamic programming, the computation required in DTW based similarity measure is polynomial in nature. (Furutuna Titus Felix, 2008). DTW was originally developed for speech recognition but it has been applied over number of applications like biometrics, finger print verification, hand writing application, shape recognition, data mining and others (Somya Adwan and Hamzah Arof, 2010).The computation cost of the DTW algorithm grows quadratic according to the length of the input sequences. DTW technique is success where time complexity is not an issue (Keogh, Eamonn J., and Michael J. Pazzani, 1999). Different supplementary techniques and modifications of DTW have been proposed by number of researchers to address the issues pertaining to DTW algorithm in certain domains (Lama, Palden and Mounika Namburu, 2010: Senin Pavel, 2008; Wang, Gang Jin, 2012). Number of researchers has studied the classical DTW algorithm, implemented and analyzed in their application of use. Since it suffers in terms of time and space complexity they have modify for its better performance and efficiency. Here in this study we have presented number of DTW algorithm which have been modified and rename as per their use.

The rest of the paper is organized as follows. Section 2 presents study of dynamic time warping algorithm. Section 3 describes a review of advanced dynamic time warping algorithm, section 4 explores another look at optimized dynamic time warping algorithm, section 5 concluded followed by references in section 6.

II. DYNAMIC TIME WARPING (DTW) ALGORITHM

Richard Bellman (1957) presented the concept of dynamic programming which has been used at very large scale in solving the optimization problems, where global optima are required. Based on dynamic programming two unequal sequences may be compare for the similarity measure which is known as dynamic time warping.

Sakoe, H. & Chiba, S. (1978) started to use the concept of DTW in speech recognition later on number of modifications have been carried out for the improvement over the existing algorithm. Classical DTW algorithm is useful and showing efficient result for small vocabulary. When database size increases the computation time increased rapidly (Berndt and Clifford, 1994; Yadav, Munshi and Afshar Alam, 2018).

Salvador, S. & Chan, P. (2007) used the concept of “Divide at Impera” method (Furutuna Titus Felix, 2008) to improve the existing DTW algorithm. They proposed solution which consists of dividing distance matrices into 2, 4, 8, 16, etc. and suggested a multilevel approach. This technique reduced the order of time complexity of DTW from quadratic to linear in time and space and improve the performance in accuracy.

Furutuna Titus Felix (2008) presented two other alternatives to implement the algorithm for pattern matching in speech recognition systems. He suggested that phase is the property of sound wave by which a human sensorial system perceived about the location of the sound. He presented the time complexity of DTW algorithm is $O(n^2v)$, where n is the length of the sequences and v is the number of words in the dictionary. Also suggested the weakness of the algorithm as it is difficult to compare the two sequences of different channels since it may have different features. It is useful only for small vocabulary (Muda Lindasalwa et al., 2010).

Double Stage DTW (DSDTW): Somya Adwan and Hamzah Arof (2010) presented a double stage DTW and experimented over face detection and it was observed that it is an efficient approach in terms of time complexity and accuracy detection. It works for similarity in image sequences when it is available in one dimensional vector. Here in this technique firstly two dimensional images will transform into one dimensional vector using image processing algorithm. After getting one dimensional vector classical DTW will apply which reduce the time complexity that is from quadratic to linear. It performs well in real time application (Yadav, Munshi and Afshar Alam, 2010).

Cuturi, Marco (2011) proposed a new technique to cost the family of DTW distances and similarities measure in time series. They explore a theoretical concept on the Global Alignment kernel. With experimental results they showed that alternative approach is faster as well as efficient than the other kernels based method on DTW. Acording to Zhu Qiang et al., (2012) ubiquity of time series data in data mining will calculate with approximation to DTW. It reduce the time complexity from quadratic to linear and used in anytime clustering concept in data mining in query by content. Table 1, summarises DTW.

Table 1: Summary of DTW

Authors	Highlights
Richard Bellman, 1957	Dynamic Programming
Sakoe, H. & Chiba, S., 1978.	Dynamic time warping algorithm in speech recognition systems.
Furutuna Titus Felix, 2008.	Alternative approaches for implementation of algorithm and the weakness of DTW.
Somya Adwan and Hamzah Arof , 2010.	A novel double stage DTW used in pattern matching for image.
Cuturi, Marco, 2011	Alternative approach as Global Alignment kernels provides faster as well as efficient results than the other kernels based on DTW.
Salvador, S., & Chan, P., 2007.	Used the concept of "Divide at Impera" method to improve the existing DTW algorithm.
Zhu Qiang et al., 2012.	An approximation in DTW helps to reduce the time complexity from quadratic to linear and used for ubiquity of time series data in data mining.

III. ADVANCED DYNAMIC TIME WARPING DTW ALGORITHM

Segmented DTW (SDTW): Keogh, Eamonn J., and Michael J. Pazzani, (1999) developed the concept of SDTW and compare the results of Euclidean Distance, DTW distance and SDTW distance. It was been found in experimental results that the DTW and SDTW are showing nearly equal results in accuracy but the SDTW is faster than DTW. The number of computations required in DTW is approximately n^2 to n^3 time more than classic DTW.

Derivative DTW (DDTW): Eamonn J Keogh and Michael J Pazzani (2001) explore the weakness of the DTW in terms of speed that is presence of continuous rise or fall in the time series. It also face problem when two sequences are differed in Y axis. The weakness of DTW is due to selections in the features that have been used. Classical dynamic time warping algorithm considers the values of the data available. In derivative DTW it is not used the data values but using the concept of different property of the shape. One of it has been calculated by first derivative of the present data sets that's why it is called as Derivative DTW. As it is a superior alignment between time series. Time complexity of DDTW is O(*mn*) which is same as DTW.

Fast Search DTW Algorithm (FDTW): Yasushi Sakurai et al. (2005) proposed a fast search DTW (FDTW) algorithm which performance is faster than existing DTW algorithm. The designing of FDTW is based on lower bound distance measure which uses the approximation in time warping distance.

Sparse DTW (SDTW): Al-Naymat et al. (2009) developed space efficient technique named as Sparse DTW for calculating the distance between two time series that always return the optimal result. It is unlike other techniques it works for space efficiency. It is observed that the space requirement will be less if the similarity between two time sequences will be more in DTW.

Qualitative DTW (QDTW): Strle. Blaz. et al. (2009) explore that in QDTW the qualitative time series has been used at the place of numerical time series. The numerical time series has been transformed to qualitative time series. Qualitative time series are shorter than the numerical time series. It is observed that when DTW algorithm is applied over this qualitative time series then it performed better in terms of speed with very less decrease in accuracy. It is also developed a qualitative approximation between QDTW and DTW.

Quantized DTW: Zaharia et al., (2010), proposed a new concept named as Quantized DTW algorithm. The merits of classical DTW and vector quantization are used here. This technique used one reference point for a particular word which will use the concept of codeword. It is observed that it reduces the space complexity significantly (Tsinaslanidis, Prodromos et al., 2014).

Weighted DTW (WDTW): Young-Seon Jeong et al., (2011) suggested that the relative phase difference between two sequences cannot be calculated using classic DTW. For this reason it is developed a weighted DTW which used the concept of penalty based DTW.

Flexible DTW (FDTW): Che- Jui Hsu et al., (2015) developed Flexible DTW adds an additional score as reward point for the continuous one-to-one matching for long fragments. The concept of flexible longest common sub-sequence (FLCS) is used in FDTW. It shows less average error rate in comparison to DTW and DDTW. It avoids comparison of coordinate points of one sequence to coordinate points of existing sequence which is far away in matching sequence (Chu, Selina et al., 2002). Table 2, summarises advanced DTW.

Table 2: Summary of advanced DTW

Authors	Highlights
Keogh, Eamonn J., and Michael J. Pazzani., 1999.	The number of computation required in Segmented dynamic time warping algorithm is very less in comparison to DTW.
Eamonn J Keogh and Michael J Pazzani , 2001.	DDTW results superior alignment between time series.
Yasushi Sakurai et al., 2005.	The performance of Fast search DTW algorithm is superior than existing DTW algorithm.
Al-Naymat et al., 2009.	Unlike other techniques the Space efficient technique named as Sparse DTW (SDTD) works for space efficiency.
Strle. Blaz. et al., 2009.	A qualitative approximation between QDTW to DTW is studied and qualitative time series is used at the place of numerical time series.
Zaharia et al., 2010.	DTW and Vector Quantization (VQ) in combination used in Quantized DTW algorithm which result the reduction in space complexity.
Young-Seon Jeong et al., 2011.	The relative phase difference between two sequences cannot be calculated using classic DTW. It can be achieve using the concept of penalty based weighted DTW.

IV. OPTIMIZED DYNAMIC TIME WARPING ALGORITHM

Multi-Stage Optimization: Mizutani Eiji (2006) explores that DTW is described as standard dynamic programming framework which is a technique that help in solving the multi-stage optimization problem, where one state is transformed to a decision by another in subsequent step. Wang et al. (2012) proposed the concept of DTW for measuring the similarities networks among various currencies in international market using different spanning tree algorithm.

Space Efficient DTW: Darabkh, Khalid A. et al. (2013) proposed an efficient DTW algorithm for Arabic Language using MFCC as feature extraction techniques and DTW as a pattern matching technique in speech recognition system. The use of delta and delta-delta coefficients improved the performance of the speech recognition in accuracy for Arabic language.

Five-Stage DTW: Yadav, Munshi and Afshar Alam (2016) presented a multi-stage DTW algorithm and used in isolated word recognition in speech and showed the order of time complexity reduces from quadratic to linear. Yadav, Munshi and Afshar Alam (2014) also showed the reduction in time complexity using multi-threading concept and result is observed in the application of speech processing systems. Table 3 summarises optimized DTW.

Table 3: Summary of optimized DTW

Authors	Description
Mizutani Eiji., 2006.	Multi-stage optimization problem, where one state is transformed to a decision by another in subsequent step using DTW.
Wang et al., 2012.	Using different spanning tree algorithm it measure the similarities of networks among various currencies in international market.
Darabkh, Khalid A. et al., 2013.	The use of delta and delta-delta coefficients which improved the performance of the speech recognition.
Yadav, Munshi and Afshar Alam (2016)	Presented multi-stage DTW algorithm with linear order of time complexity in the application of speech recognition systems.
Yadav, Munshi and Afshar Alam (2014)	The use of DTW with multi-threading concept showed reduction in computation.

V. CONCLUSIONS

We presented in details about the study of deferent types of dynamic time warping algorithm like sparse DTW, fast DTW, derivative DTW, iterative DTW, quantized DTW, qualitative DTW, iterative deepening DTW etc,. A look is made in the review of literature for performance of algorithms in terms of efficiency, time and space complexity.

ACKNOWLEDGEMENT

We would like to express our sincere thanks to Dr. Abdul Mobin, Ex. Chief Scientist, National Physical Laboratory, Delhi, for his valuable guidance and sincere advise without which it could not be possible to complete the work presented in this paper.

VI. REFERENCES

[1]. Al-Naymat, Ghazi, Sanjay Chawla, and Javid Taheri. "Sparsedtw: A novel approach to speed up dynamic time warping." In *Proceedings of the Eighth Australasian Data Mining Conference-Volume* 101, pp. 117-127. Australian Computer Society, Inc., 2009.

[2]. Berndt, D. J., & Clifford, J. (1994, July). "Using dynamic time warping to find patterns in time series". In *KDD Workshop* Vol. 10, No. 16, pp. 359-370.

[3]. Che-Jui Hsu , Kuo- Si Huang, Chang-Biau Yang and Yi-Pu Guo, "Flexible Dynamic Time Warping for Time Series Classification." In International *Conference on Computational Science* ICCS -2015, Vol. 51, pp 2838-2842. Doi: 10.1016/J. procs.2015.05.444.

[4]. Chu, Selina, Eamonn Keogh, David Hart, and Michael Pazzani. "Iterative deepening dynamic time warping for time series." In *Proceedings of the 2002 SIAM International Conference on Data Mining*, pp. 195-212. Society for Industrial and Applied Mathematics, 2002.

[5]. Cuturi, Marco. "Fast global alignment kernels." In *Proceedings of the 28th international conference on machine learning (ICML-11)*, pp. 929-936. 2011.

[6]. Darabkh, Khalid A., Ala F. Khalifeh, Baraa A. Bathech, and Saed W. Sabah. "Efficient DTW-based speech recognition system for isolated words of Arabic language." In *Proceedings of International Conference on Electrical and Computer Systems Engineering (ICECSE 2013)*, pp. 689-692. 2013.

[7]. Furtuna, Titus Felix. (2008), "Dynamic programming algorithms in speech recognition". *Revista Informatica Economică* nr 2, no. 46, 94.

[8]. Keogh, Eamonn J., and Michael J. Pazzani. "Derivative dynamic time warping." In *Proceedings of the 2001 SIAM International Conference on Data Mining*, pp. 1-11. Society for Industrial and Applied Mathematics, 2001.

[9]. Keogh, Eamonn J., and Michael J. Pazzani. "Scaling up dynamic time warping to massive datasets." In *European Conference on Principles of Data Mining and Knowledge Discovery*, pp. 1-11. Springer, Berlin, Heidelberg, 1999.

[10]. Lama, Palden, and Mounika Namburu. "Speech recognition with dynamic time warping using MATLAB." *Project Report, CS 525*, Springer 2010.

[11]. Mizutani, Eiji., "The Dynamic Time Warping Algorithms." *Mechanical Engineering Seminar, Tokyo Metropolitan University*. 2006.

[12]. Muda, Lindasalwa, Mumtaj Begam, and Irraivan Elamvazuthi. "Voice recognition algorithms using mel frequency cepstral coefficient (MFCC) and dynamic time warping (DTW) techniques." *arXiv preprint arXiv:1003.4083* (2010)

[13]. R. E. Bellman, "Dynamic Programming," *Princeton University Press, Princeton, New Jersey, USA*, 1957.

[14]. Sakoe, H., & Chiba, S. "Dynamic programming algorithm optimization for spoken word recognition." *IEEE transactions on acoustics, speech, and signal processing*, 26(1), pp-43-49, 1978.

[15]. Salvador, S., & Chan, P. (2007). "Toward accurate dynamic time warping in linear time and space." *Intelligent Data Analysis*, 11(5), 561-580.

[16]. Senin, Pavel. "Dynamic time warping algorithm review." *Information and Computer Science Department University of Hawaii at Manoa Honolulu, USA* 855 (2008): pp. 1-23.

[17]. Somya Adwan and Hamzah Arof, "A Novel Double Stage Dynamic Time Warping Algorithm for Image Template Matching," *6th IMT-GT Conference on Mathematics. Statistics and its Applications (ICMSA 2010), University Tunku Abdul Rahman, Kuala Lumper, Malaysa*. pp 667-667-676.

[18]. Strle, Blaz, Martin Mozina, and Ivan Bratko. "Qualitative approximation to Dynamic Time Warping similarity between time series data." *Proc. QR* (2009).

[19]. Tsinaslanidis, Prodromos, Antonis Alexandridis, Achilleas Zapranis, and Efstratios Livanis. "Dynamic time warping as a similarity measure: applications in finance." *no. Journal Article* (2014).

[20]. Wang, Gang-Jin, Chi Xie, Feng Han, and Bo Sun. "Similarity measure and topology evolution of foreign exchange markets using dynamic time warping method: Evidence from minimal spanning tree." *Physica A: Statistical Mechanics and its Applications* 391, no. 16 (2012): 4136-4146.

[21]. Y.-S. Jeong, M. K. Jeong, and O. A. Omitaomu. "*Weighted dynamic time warping for time series classification. Pattern Recognition,"* 44(9): pp- 2231–2240, 2011.

[22]. Yadav, Munshi and Afshar Aalam. "Five Stage Dynamic Time Warping Algorithm for Speaker Dependent Isolated Word Recognition in Speech." *International Journal of Computer and Software Engineering (IJCSE)*, (2016). Volume-4, Issue-10, pp. 112-115.

[23]. Yadav, Munshi and Afshar Aalam."Speech Recognition: A Review." *International Journal of Electronics and Computer Engineering (IJECE).*Vol. 6, Issue 1 Jan-Mar. 2018, pp. 481-489.

[24]. Yadav, Munshi and Afshar Alam. "Reduction of Computation Time in Pattern Matching for Speech Recognition." *International Journal of Computer Applications* 90, No. 18 (2014). pp. 35-37.

[25]. Yadav, Munshi and Afshar Alam. "A Novel Method for High Performance Computing in Speech Recognition", *International Conference on Next Generation Communication and Computing Systems (ICNGC2S-10)*, December 25-26, 2010, Chandigarh, India. pp. 345 - 347.

[26]. Yasushi Sakurai, Masatoshi Yoshikawa Christos Faloutsos, "FTW: Fast Similarity Search under the Time Warping

Distance", *PODS* 2005, June 13-15, 2005, Baltimore, Maryland. ACP 1 - 59593 - 062- 0/05/06. pp 1-11.

[27]. Zaharia, Tiberius, Svetlana Segarceanu, Marius Cotescu, and Alexandru Spataru. "Quantized dynamic time warping (DTW) algorithm." *In Communications (COMM), 2010 8th International Conference on*, pp. 91-94. IEEE, 2010.

[28]. Zhu, Q., Batista, G., Rakthanmanon, T., & Keogh, E. (2012, April). "A novel approximation to dynamic time warping allows anytime clustering of massive time series datasets." In *Proceedings of the 2012 SIAM International Conference on Data Mining* pp. 999-1010. Society for Industrial and Applied Mathematics.

Author has been Graduated in Electronics and Communication Engineering from Govind Ballbh Pant Engineering College, Pauri Garhwal, Uttrakhand, University of H. N. Bahuguna Garhal Central University, Srinagar Garhwal, Uttrakhand. Post Grudated in Information Technology from University School of Information Technology, Guru Govind Singh Indraprastha Univesrsity, Delhi. Purusing PhD in Computer Science & Engineering from School of Engineering Sciences and Technology, Jamia Hamdard, Delhi.