An End-to-End System for Bangla Online Handwriting Recognition

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***Abstract*—A few studies of online Bangla handwriting recognition such as isolated character recognition or limited vocabulary cursive word recognition are found in the literature. However, development of an end-to-end recognition system of unconstrained online Bangla handwritten texts has not been duly attempted so far. In the present report, we describe a similar system which takes a piece of continuous online handwritten Bangla texts as the input. It first segments the input texts into individual lines, each line into its constituent words and each word into sub-strokes. In the present study, 152 different symbols which include basic characters, character modifiers, frequently used conjunct characters, a few special characters and numerals have been considered. The entire set of sub-strokes obtained from the training sample set has been exhaustively studied by 3 experts and 76 different shapes of sub-strokes have been identified based on consensus among these experts. Also, it has been observed that a character may produce at most 3 sub-strokes. Since a piece of Bangla texts often contains either Bangla or English numerals, the present character set consists of both the numeral set and 3 numeral shapes are common to both the scripts. The proposed recognition system uses two classifiers, one for characters and the other for sub-strokes. Sub-strokes are fed to the character classifier in their temporal order. A single sub-stroke followed by two consecutive sub-strokes and finally three successive sub-strokes are passed to the character classifier and the first two top responses of the character classifier among the three cases are compared. If the difference is less than a threshold, the response of sub-stroke classifier is used to reach a final decision. The proposed system provided 94.3% character level accuracy on a test set consisting of 33,453 word samples written by 31 writers.**

I. Introduction

Online handwriting recognition research has now gained significant relevance due to the recent outspread of electronic tablets and similar devices enabled with handwriting based input. Extensive research studies on online handwriting recognition of various scripts such as Latin, Arabic, Chinese, Korean, Japanese etc. can be found in the literature [1], [2], [3], [4], [5], [6], [7], [8]. Efficient recognition systems of several of these scripts are also available in the market. However, this scenario is different as far as Indian scripts are concerned. There have been several studies [9], [10], [11], [12], [13] of online handwriting recognition of a few Indian scripts. However, a majority of them had dealt with isolated characters only. Recently, in a very few works [14], [15], [16], [17], [18] limited lexicon recognition of online handwritten words of major Indian scripts such as Devanagari, Bangla and Tamil have been studied. Also, lexicon free recognition of Devanagari and Tamil online handwriting had been studied in [17], [18]. A few years back, preliminary recognition studies [19], [20] of lexicon free online Bangla handwriting were done although the scope of this study was very limited mainly due to the availability of only limited sample data. However, the situation has changed in the intervening period. A large database of online unconstrained handwritten Bangla texts has now been developed and those are semi-automatically annotated [21] for its subsequent recognition study.

In the present article, we describe our recent development of an end-to-end system of recognition of continuous online handwritten Bangla texts. A block diagram of the same is shown in Fig. 1. It integrates a few modules in a series such as (i) line segmentation, (ii) word segmentation, (iii) word preprocessing, (iv) stroke segmentation, (v) sub-stroke and character recognition, (vi) formation of the Unicode sequence of the word and finally (vii) postprocessing operations. We use support vector machine (SVM) as the classifier for both sub-stroke and character recognitions.

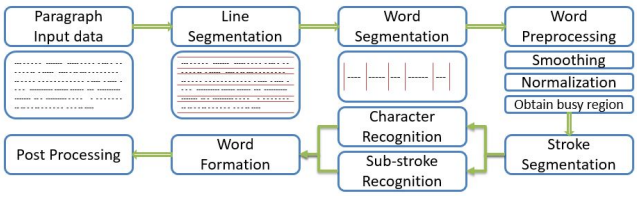

Fig. 1. Block diagram of the proposed end-to-end recognition system

The rest of this article is organized as follows. In the next Section, we shall briefly describe the character set involved in the continuous text data used in the present study. Section III presents different modules of the proposed end-to-end recognition system. Experimental results are presented in Section IV. Section V concludes this article.

II. Character Set Used in the Present Study

Bangla alphabet has 50 basic vowel and consonant characters and another 11 modified shapes of several of its basic characters. In addition to these 61 basic and modified shapes, its alphabet consists of a large number of conjunct characters. Shapes of several of these conjunct characters are

2167-6445/16 $31.00 © 2016 IEEE
DOI 10.1109/ICFHR.2016.71

Fig. 2. Bengali character set used in the present study

just horizontal or vertical adjoining of two basic characters while in a large number of cases the conjunct characters have completely different shapes from their constituent characters. However, a large number of these conjunct characters occur only rarely in any text corpus. In the present study, we consider only 64 of these conjunct characters. Since a common Bangla writer intermittently uses both Bangla and English numerals, in the present system we consider both of them. Three numeric shapes are common to both English and Bangla and hence the present character set includes 17 different numeric shapes in addition to shapes of 10 special characters. Thus, the proposed end-to-end Bangla handwritten text recognition system handles a set of 152 different characters. These character shapes are shown in Fig. 2. The only existing study [19] of analytic recognition of unconstrained mixed cursive Bangla handwriting, considered only 60 of these characters which included basic and modified shapes of Bangla characters.

III. Proposed Analytic Recognition Mechanism

The proposed end-to-end recognition system consists of segmentation of continuous texts at line, word and sub-stroke levels. The line segmentation is comparatively straight forward. On the other hand, both word and sub-stroke segmentations are difficult tasks.

A. Line Segementation

Although online handwriting data carry more information than its offline counter part such as the temporal information, it has more variability than offline handwriting data mainly because of the presence of delayed strokes. The problem may occur when a modifier appears either below or above another character of the middle region. For example, consider the three handwritten Bangla text lines in Fig. 3 where the first two lines are the last parts of a paragraph while the third line is the beginning of the next paragraph. The first character in the second line has a vowel modifier at the bottom while there is a vowel modifier at the top of the second character in the third line. Here it is quite possible that the bottom most point in the first modifier may have a larger y-value than that of the top most point in the second modifier. Also, it is possible that the first modifier is temporally the last stroke of the second line. In such cases, from the temporal information of the last stroke of a line and the first stroke of the next line, it is sometimes difficult to determine that there is in fact a line break. Line segmentation is done here using both online and offline information of the data.

B. Word Segementation

In this module, we compute the horizontal distance between each pair of positions corresponding to successive pen-up and pen-down situations along the pen trajectory in each line of the whole document page and take their average. If such an individual distance is greater than the overall average distance, the vertical line through the middle of the corresponding horizontal stretch of the pen trajectory is considered as the line of segmentation between two consecutive words belonging to the same line. The result of line and word segmentation of a piece of continuous handwritten texts by the proposed system is shown in Fig. 4.

C. Preprocessing

Online handwritten signal captured by a tablet is often affected by various noise. Also, the handwriting styles of different writers vary extremely widely. So, a set of preprocessing operations is often applied on such handwritten words before further processing. In the present system, the following set of preprocessing operations has been applied (i) removal of duplicate points, (ii) normalization of word height to a fixed value (200 units) keeping the aspect ratio unchanged and (iii) smoothing of strokes by 3-point moving average.

D. Stroke Segementation

The proposed recognition system includes a module for possible segmentation of strokes in a word into two or more sub-strokes. Segmentation of mixed cursive Bangla words was studied earlier in [15], [19]. However, these existing segmentation approaches often cause too much over-segmentation which is difficult to tackle by the following modules of the proposed system. Thus, for the proposed end-to-end recognition system, we have designed a modified scheme for possible segmentation of online mixed

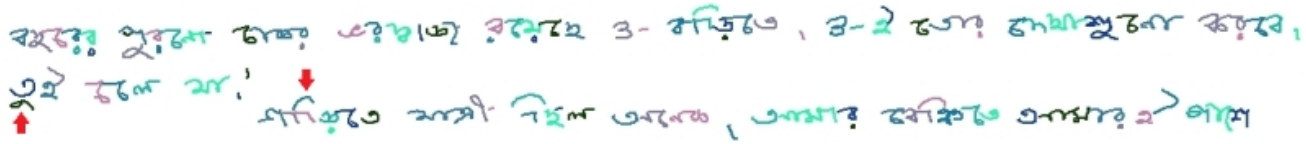

Fig. 3. Difficulties in line segmentation may sometimes be caused by occurrence of delayed strokes and modifiers occurring on the top of or below (shown by red arrows) a character of the middle zone.

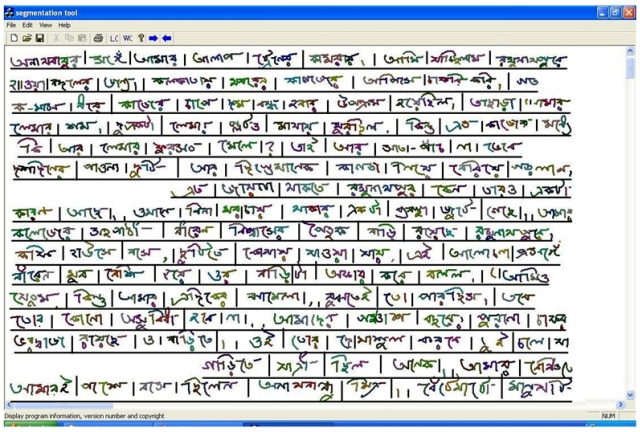

Fig. 4. A piece of continuous Bengali handwritten texts is line and word segmented as above. Change of color in a word signifies pen-up followed by pen-down.

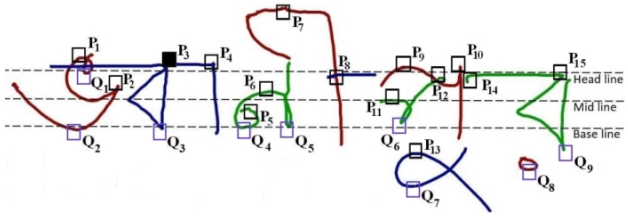

Fig. 5. The minima and maxima points of a handwritten Bangla word sample are respectively marked with black and blue rectangles denoted by $\{P_1, P_2 \ldots, P_{15}\}$ and $\{Q_1, Q_2, \ldots, Q_9\}$.

cursive Bangla words into sub-strokes avoiding both under-segmentation and too much over-segmentation. This stroke segmentation module is preceded by detection of three zones in a Bangla word. In fact, most of the Bangla words have three specific horizontal zones such as upper, middle and lower zones and these are determined by two imaginary lines called the 'headline' and 'baseline'. Although estimation of these two lines is not a very difficult task in case of printed texts, the situation is different for handwritten texts.

1) Zone Detection: Input to this module is a word sample, i.e., a temporal sequence of points $W = \{(x_i, y_i)|i = 1, 2, \ldots, n\}$, where n is the total number of sample points of the sequence of strokes forming the word sample. Here, we first determine the maxima and minima points of W. A non-terminal point $P(x_i, y_i)$ of a stroke in W is said to be a minima point iff $y_{i-1} > y_i < y_{i+1}$ while this point P is said to be a maxima point iff $y_{i-1} < y_i > y_{i+1}$. In Fig. 5, $P_1, P_2, \ldots, P_{15}$ are the minima points and $Q_1, Q_2, \ldots, Q_9$ are the maxima points. Now we consider division of the word sample into N (here, value of N is empirically decided as 6) horizontal slices $G_i, i = 1, 2, \ldots, N$ of equal heights and determine the slices G_j and G_k $(j < k)$ containing respectively the maximum numbers of minima and maxima points. The horizontal line corresponding to the average of the y-coordinates of the minima points lying in G_j determines the headline and the average of the y-coordinates of the maxima points of G_k determines the baseline. If tie occurs, then the upper or the lower one among the ties are respectively determined as the headline or baseline. Another imaginary line passing through the mean of the above two averages of y-values is called the 'middle line'. Now, the part of a Bangla word sample lying above the headline is called the upper zone, and the part below the baseline is called the lower zone whereas the zone between these two is the middle zone.

2) Segmentation Point Determination: The proposed approach to selection of segmentation points is primarily based on the following observations.

- A large majority of Bangla characters (except possibly a few modifiers) initiates from a point near the headline and extends till near the baseline.
- Occurrence of headline (a common feature of many Indic scripts) in handwritten Bangla word is extremely irregular.
- A few modifiers always occur below the baseline or above the headline.
- Bengali characters (except a few modifiers) always have their parts in middle zone.
- Modifiers which entirely or partly occur above the headline or below the baseline are usually followed by a pen-up condition.

Based on the above observations, we define a 'head zone' which extends an height of $\frac{H}{10}$, (H= normalized height of the word) above and below the headline. Now, a minima point of Section III-D1 is a candidate point provided it lies in the head zone. In the proposed algorithm, decision for segmentation at a candidate point is taken based on a set of data driven conditions. This segmentation algorithm is detailed below.

In Fig. 5, $P_1, P_3, P_4, P_8, P_9, P_{10}, P_{12}, P_{14}$ are the candidate points and P_3 (marked by solid black rectangle) is the only valid segmentation point. A segmentation point splits a stroke into two substrokes.

for *each candidate point* P_k **do**
  Check for its immediate left and right next maxima (before having the next left or right minima) in the same stroke,
  say $P_{maxima_{left}}$ and $P_{maxima_{right}}$.
  if *both* $P_{maxima_{left}}$ *and* $P_{maxima_{right}}$ *reside below* $Y_{midline}$ **then**
    P_k is a valid segmentation point.
  else
    if $P_{maxima_{left}}$ *below* $Y_{midline}$ *and* $P_{maxima_{right}}$ *above* $Y_{midline}$ **then**
      P cannot be a valid segmentation point. (case ক, ফ etc)
    else
      if $P_{maxima_{left}}$ *above* $Y_{midline}$ *and* $P_{maxima_{right}}$ *below* $Y_{midline}$ **then**
        if $P_{maxima_{left}}$ *is the* 1^{st} *maxima of that stroke* **then**
          P_k is valid segmentation Point. (Case ত, অ, আ etc)
        else
          P_k is not a valid segmentation point. (Case cursive)
        end
      else
        P_k is not a valid segmentation point.
      end
    end
  end
end

Algorithm 1: Pseudocode for Segmentation

E. Headline Removal

Since the headline of a Bangla handwritten word occurs irregularly and does not carry any useful information, in the proposed recognition scheme, the substrokes that lie around the headline as defined above are identified as much as possible before stepping into the next module. Such identification is based on the maximum difference between the y-values of the points on a substroke and the y-value that defines the headline. If this maximum difference is less than an empirically determined value, the substroke is removed. The word sample shown in Fig. 5 is obtained after segmentation and it has only one substroke satisfying the above criterion. Fig. 6 shows the sample after the removal of this substroke.

F. Recognition Module

Input to this module is the segmented word sample obtained as the output of the previous module. The task in this module is to form the individual characters from the sequence of substrokes. In the proposed approach, we consider two classifiers - (i) one for the characters and (ii) the other for the substrokes. The training word samples are segmented and manually annotated at character levels. So, we have all the character samples obtained from these annotated training word samples and these are used to train the character classifier. On the other hand, the segmented sub-strokes are manually studied by three experts and 76 different shapes of sub-strokes were identified based on consensus among them. The substroke samples are segregated into 76 folders to train a substroke classifier.

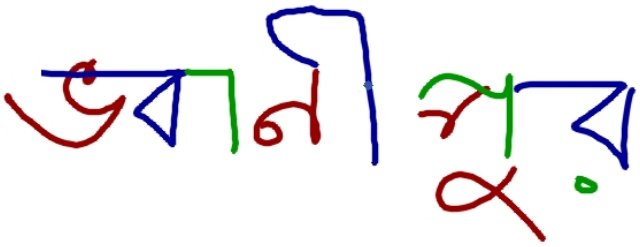

Fig. 6. A Bangla word is segmented and headline removed by the proposed approach.

1) Classification: In the proposed end-to-end system, we have used Support Vector Machine (SVM) [16] with Radial Basis Function (RBF) kernel as the common classifier for both character set and substroke set. The character classifier handles a 152 (11 basic vowels, 39 basic consonants, 11 modifiers, 64 conjunct characters, 17 numerals and 10 special characters) class classification problem whereas the substroke classifier considers 76 different classes. For classification, we consider a set of features which were used by us in one of our earlier studies [16] on limited vocabulary online Bangla handwritten word recognition.

2) Feature Computation: Feature vector is computed for both substroke and character samples. Each type of these input samples is first divided into 3 segments as follows. For segmentation of a substroke sample into three pieces, we need to find on it two points having two most sharp turns. If ties occur, then creation of a comparatively smaller piece is avoided. On the other hand, if a character is formed of 3 sub-strokes, no further division of it is required. If a character sample is composed of 2 substrokes, then the larger one is divided into two pieces of equal length, and if a character is composed of only one substroke, then two points on it are obtained corresponding to the most sharp turns as in the case of a single substroke. Since none of the character samples in our database is composed of more than three substrokes, no merging operation is required. Next, each such piece of trajectory is re-sampled to 8 points such that both the initial and terminal points are preserved and another six points are computed on the trajectory of the piece such that the distance between two such consecutive re-sampled points remains approximately the same.

3) Feature Components: From a substroke or a character sample, we obtain four feature vectors F_1, F_2, F_3 and F_4. Feature F_1 consists of the quantities: (i) differences in the respective x and y coordinate values of the initial and terminal points of each piece of trajectory, producing 6 quantities, (ii) aspect ratio of the input sample, (iii) 3 aspect ratios of three pieces of trajectory, and (iv) length of the entire trajectory of the input word sample. Thus, the feature vector F_1 has 11

এ	অ, ঐ, ক্ৰ, ঞ	ঘ	ক্ষ	ত	অ, আ, ত্ব	ফ	ফ্র, য়	য, ষ	ষ্ঠ	ো	ি, ী, ৌ
এ, অ	আ	ঙ	ঙ্ক, ঙ্খ, ঙ্গ	ত, অ	আ	ব	ক, ঝ, ধ, ন্দ, ব্ব, ব্র, র, য়	য, ষ	ষ্ণ	স	ন্ত, হ্ন
ও	অ, অ, উ, ঔ, ক্ত, ক্ত, ক্ত, জ, ঞ, ত্ব	চ	চ্ছ, ট	থ	ঞ্চ	ব, ঝ	ঋ	ল	ল্প, ল্ভ, ল্ল, ল্ম	১	গ, শ, স, স, স
ও, অ	আ	ড	অ, উ, ঔ, গ, জ, ঞ, স, ড়	দ	গ, দ্দ, দ্ধ, দ্ব, ন্দ	ব, ক	ক্ক	শ	ক্ষ, শ্চ, শ্ব, শ্ম, শ্র	১, গ	থ্ব
ো	খ, ি, ী, ৌ, ড, দ্ব, প, প, প্র,	ড, অ	আ	দ, গ	থ্ব	ব, ক	ক্ল	স	ন্ত, হ্ন	২	ই
ো, প	প্প	ড, উ	ঊ	দ, দ্ব	দ্ধ	ব, র	রু	হ	ই, ঈ, স	৩	অ, অ, আ
ে	ংং, গ, ৈ, ট, স	ড, ঔ	ঋ	দ, ন্দ	ন্দ্র	ভ	ড়	ৎ	স	৩, অ	আ
ে, গ	থ্ব,	ড, গ	থ্ব	ন	ঞ্চ, ণ্ড, ন্ড, ন্ত, ন্ত, ন্ত্র, ন্ম, ন্দ, ন্ধ	ম	ক্ষ, ম্ব, ম্ভ, ম্ল, শ, ক্ষ	দ্র	ন্দ্র	৪	গ, স, স
ক	ক্ক, ক্ল, ঞ্চ, শ	ড, জ	জ্ঞ	ন, ণ্ড	জ্ঞ	ম, শ	শু	য্য	গ, জ, স	৪, গ	থ্ব
খ	শ্র	চ	ছ, ট, ঢ়	ন, ন্দ	ন্দ্র	য	ষ, য়, য়, র	য্য, গ	থ্ব	৬	উ, জ
গ	থ্ব, ণ্ড, থ্র	চ, ট	ট্ট	প	প্ট, প্প, প্র, প্ল	য, ফ	ফ্র	ো	র্, ংং, ি, ী, ৌ	৮	ট

Fig. 7. Reference table for character formation from sub-strokes

components.

Feature F_2 is composed of the directional information of the pen movement at each point save for the last point of each of the 3 pieces of trajectory. These are computed as the sine and cosine of the angles that are made with the positive x-axis while moving from one re-sampled point to the next. Thus, F_2 feature vector has 14 (2×7) components from each individual piece of trajectory and hence has 42 (3×14) components from the entire input sample.

Feature F_3 consists of the numbers of re-sampled points of the input sample (i) lying above and below the horizontal line and (ii) to the left and to the right of the vertical line passing through each point. Thus, each re-sampled point produces 4 quantities so that F_3 has 96 ($4 \times 8 \times 3$) components.

Feature F_4 computes second order differences between the coordinates of the successive re-sampled points along each piece of the input trajectory. Thus, it computes two (x and y) values at each point except the first and last points of each piece of the input sample. So, F_4 has 36 ($2 \times 6 \times 3$) components.

The features in F_1, F_2, F_3 and F_4 are concatenated and the resulting 185 (11+42+96+36) component feature vector is fed as input to both the SVM-based stroke and character classifiers.

4) Reference Table: We developed a reference table based on a detailed study of the segmented training character samples. These samples show the nature of combinations of various substrokes forming different members of the present character set. It often happens that a valid character combined with one or more substrokes forms another valid character. So, during automatic recognition of characters in a continuous handwritten Bangla texts, such a knowledge base plays a major role. This reference table is shown in Fig. 7. In the third column of the first row of Fig. 7, an entry ত with অ, আ and ত্ব implies that if a substroke is recognized as ত then it may further get associated with other substrokes to be finally recognized as অ, আ or ত্ব.

5) Character Formation: The feature vector of a substroke is fed to both the character classifier and the substroke classifier. If the difference between the first two maximum responses of the character classifier is greater than or equal to an empirically fixed threshold value δ, the substroke is classified as the character having the largest response. However, if this difference is less than δ, we compare its first maximum response with the same of the substroke classifier and the class corresponding to the greater value of these two maxima is considered as the recognized class. If the recognized class is not a valid character, then we combine the next substroke with the previous one to feed the combined substroke to the character classifier and the next substroke alone is fed to the substroke classifier. Similar checking is done again. If a valid character is formed, then we consult the reference table of Fig. 7 to verify whether there is the requirement of further combining the next substroke and feed the same to the classifiers to check whether the maximum response increases forming another character. We combine a maximum number of 3 substrokes to feed into the character classifier since our training set does not have any sample which is formed by more than three substrokes.

(i) (ii)

Fig. 8. (i) an original Bangla word containing 3 strokes S1, S2 and S3 (ii) its segmented form containing 7 sub-strokes S1, S2, ..., S7

As an example, we consider Fig. 8 (ii). Here, substroke S_1 recognized as ত with maximum response D_1. Now it is found in the reference table Fig. 7 (1st row, 3rd column), ত has an association with (অ, আ, ত্ব), thus S_1 and S_2 both are passed into the character classifier. Now it recognized as অ with maximum response $D_2 > D_1$. Again from the reference table, an association is found (2nd row, 3rd column) thus S_1, S_2 and S_3 are passed into the character classifier. Now it is recognized as আ with response $D_3 < D_2$. Thus, the character output অ formed by the sub-strokes S_1 and S_2 has the maximum response. So, the current classification result is অ and the same process is repeated with the substroke S_3 which is next recognized as া.

G. Checking of Bangla Script Specific Rules

The above analytic recognition scheme produces a sequence of valid character class labels for an input word sample.

Finally, the proposed end-to-end system checks a few Bangla script specific modification rules needed a few character outputs. These rules are as follows.

Case 1 অ + া → আ

Case 2 ে + (a basic or conjunct character) + া → ো with that basic or conjunct character, e.g., ে + ব + া → বো

Case 3 ে + (a basic or conjunct character) + ৗ → ৌ with that basic or conjunct character, e.g., ে + ব + ৗ → বৌ

Case 4 When two basic components appear one below the other and both are classified as some consonants then they together form a conjunct character, e.g., ল + ল → ল্ল, দ + ব → দ্ব, ন + ত → ন্ত etc

Case 5 When two basic components appear one intersecting the other then চ + চ → চ্চ, চ + ছ → চ্ছ, ব + ব → ব্ব, ড + ড → ড্ড, ল + ট → ল্ট, ব + দ → ব্দ, স + ত → স্ত

Case 6 If there is a dot shape below the mid line then if the previous recognized character is one of the possible characters having a dot, then we form the character accordingly. For example, ব + . → র, য + . → য়, ড + . → ড়, ঢ + . → ঢ়

In Fig. 8, the character sequence that the classifier outputs is 'অ' 'া' 'ব' 'া' 'র'. Now Case 1 shows that অ + া → আ. Thus, the final output character string becomes আবার.

IV. Experimental Results

The proposed end-to-end online Bangla handwriting recognition approach has been trained and tested on large databases of different levels such as continuous text data, isolated word data, character level and sub-stroke level data. 62 pages of continuous text data were collected from 31 writers with necessary ground truth. The proposed approach provided more than 99% accuracy at line segmentation level and approximately 98.4% at word segmentation level. In addition to this continuous text data, we used 96184 character data and 54927 sub-stroke data for training character level and sub-stroke level classifiers. These character and sub-stroke samples were divided into training and validation samples. The final trained end-to-end system was tested on the entire database of continuous texts and obtained 94.3% accuracies at character level. In [19], 98.2% word level segmentation accuracy and in [20] 88.5% character level recognition accuracy were obtained on different Bangla datasets.

V. Conclusion

"Bengali Handwritten Keyboard Application", an Android based version of the word recognition part of the proposed system is downloadable from the Indian Language Technology Proliferation and Deployment Centre web site (http://tdil-dc.in/index.php?option=com_download&task=showresourceDetails&toolid=1732&lang=en [last accessed on 31 July, 2016]). A copy of the proposed end-to-end system may be obtained by sending requests through emails to any one of the authors.

Acknowledgment

This research work has been partially supported by a grant from the TDIL group of the Dept. of Information Technology, Govt. of India.

References

[1] D.-H. Wang and C.-L. Liu, Learning Confidence Transformation for Handwritten Chinese Text Recognition, Int. Journ. on Doc. Anal. and Recog., vol. 17(3), pp. 205-219, 2014. 1

[2] L. Haddad, T. M. Hamdani, and A. M. Alimi, OHRS-MEWA: On-Line Handwriting Recognition System with Multi-environment Writer Adaptation, Proc. of 14th Int. Conf. on Frontiers in Handwriting Recog., pp. 335–340, 2014. 1

[3] J. Sternby, J. Morwing, J. Andersson, and C. Friberg, On-line Arabic Handwriting Recognition with Templates, Pattern Recognition, vol. 42, pp. 3278-3286, 2009. 1

[4] M. Nakagawa, M. J. Tokuno, B. Zhu, and M. Onuma, Japanese Handwriting Recognition and Its Applications, Proc. of Conf. on Arabic and Chinese Handwriting Recog., pp. 170-195, 2006. 1

[5] C.-L. Liu, S. Jaeger, and M. Nakagawa, Online Recognition of Chinese Characters: The State-of-the-Art, IEEE Trans. on Patt. Anal. and Mach. Intell., vol. 26(2), pp. 198-213, 2004. 1

[6] S. Jaeger, L. C. Liu, and M. Nakagawa, The State-of-Art in Japanese Online Handwriting Recognition Compared to Techniques in Western Handwriting Recognition, Int. Journ. of Doc. Anal. and Recog., vol. 6(2), pp. 75-88, 2004. 1

[7] R. Plamondon and S. Srihari, Online and Off-line Handwriting Recognition: A Comprehensive Survey, IEEE Trans. on Patt. Anal. and Mach. Intell., vol. 22, pp. 63-84, 2000. 1

[8] K. Jung, S. Yoon, and H. Kim, .Continuous HMM Applied to Quantization of On-line Korean Character Spaces, Pattern Recognition Letter, vol. 21(4), pp. 303-310, 2000. 1

[9] A. Bharath, and S. Madhvanath, Allograph modeling for online handwritten characters in Devanagari using constrained stroke clustering, ACM Trans. on Asian Language Info. Proc., vol. 13(3), pp. 1-12, 2014. 1

[10] S. K. Parui, K. Guin, U. Bhattacharya, and B. B. Chaudhuri, Online Handwritten Bangla Character Recognition Using HMM, Proc. of 19th Int. Conf. on Pattern Recog., pp. 1-4, 2008. 1

[11] S. Sundaram and A. Ramakrishnan, Two Dimensional Principal Component Analysis for Online Tamil Character Recognition, Proc of 11th Int. Conf. on Frontiers in Handwriting Recog., pp. 88-94, 2008. 1

[12] U. Bhattacharya, S. K. Ghosh and S. K. Parui, A Two Stage Recognition Scheme for Handwritten Tamil Characters, Proc. of 9th Int. Conf. on Doc. Anal. and Recog. pp. 511-515, 2007. 1

[13] H. Swethalakshmi, A. Jayaraman, V. S. Chakravarthy, and C. C. Sekhar, Online Handwritten Character Recognition of Devanagari and Telugu Characters Using Support Vector Machines, Proc. of 10th Int. Workshop on Frontiers in Handwriting Recog., pp. 367-372, 2006. 1

[14] S. Sundaram, and A. G. Ramakrishnan, Bigram language models and reevaluation strategy for improved recognition of online handwritten Tamil words, ACM Trans. on Asian and Low-Resource Language Information Processing, vol. 14(2), pp. 1-8, 2015. 1

[15] O. Samanta, U. Bhattacharya, and S. K. Parui, Smoothing of HMM Parameters for Efficient Recognition of Online Handwriting, Pattern Recog., vol. 47(11), pp. 3614-3629, 2014. 1, 2

[16] A. Srimany, S. D. Chowdhuri, U. Bhattacharya, and S. K. Parui, Holistic Recognition of Online Handwritten Words Based on an Ensemble of SVM Classifiers, Proc. of Int. Workshop on Doc. Anal. Sys., pp. 86-90, 2014. 1, 4

[17] S. Sundaram and A. G. Ramakrishnan, Attention-Feedback Based Robust Segmentation of Online Handwritten Isolated Tamil Words, ACM Trans. on Asian Language Info. Proc., vol. 12(1), pp. 4:1 - 4:25, 2013. 1

[18] A. Bharath and S. Madhvanath, HMM-based Lexicon-driven and Lexicon-free Word Recognition for Online Handwritten Indic Scripts, IEEE Trans. on Patt. Anal. and Mach. Intell., vol. 34(4), pp. 670-682, 2012. 1

[19] U. Bhattacharya, A. Nigam, Y. S. Rawat, and S. K.Parui, An Analytic Scheme for Online Handwritten Bangla Cursive Word Recognition, Proc. of Int. Conf. on Frontiers in Handwriting Recog., pp. 320-325, 2008. 1, 2, 6

[20] G. Fink, et al., Online Bangla word recognition using sub-stroke level features and hidden Markov models, Proc. of Int. Conf. on Frontiers in Handwriting Recog., pp. 393-398, 2010. 1, 6

[21] U. Bhattacharya, et al., A semi-automatic annotation scheme for Bangla online mixed cursive handwriting samples, Proc. of Int. Conf. on Frontiers in Handwriting Recog., pp. 676-681, 2012. 1