Combining On-Line and Off-Line
Bidirectional Long Short-Term Memory Networks
for Handwritten Text Line Recognition

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Abstract

In this paper we present a multiple classifier system (MCS) for on-line handwriting recognition. The MCS combines several individual recognition systems based on bidirectional long short-term memory networks. To obtain diverse recognizers, we use different feature sets based on on-line and off-line features. Furthermore, we generate a number of different recognizers by changing the initialization of the networks. To combine the word sequences output by the recognizers, we incrementally align these sequences using the recognizer output voting error reduction framework (ROVER). For deriving the final decision, different voting strategies are applied. The best combination ensemble has a recognition rate of 83.64%, which is significantly higher than the 81.26% achieved by the best individual classifier.

1. Introduction

Although the problem of handwriting recognition has been considered for more than 40 years [2, 15, 19], there are still many open issues, especially in the task of unconstrained handwritten sentence recognition. In this paper we consider the recognition of text written on a whiteboard, which is a relatively new task. Recently, a novel recognition strategy based on bidirectional long short-term memory networks (BLSTM) has been presented for this problem [13]. This approach uses connectionist time classification (CTC) to allow the underlying neural networks to be trained and tested on unsegmented data.

Having the on-line and the off-line recognition systems described in [13] and [12] available, it may be beneficial to combine both systems. From such a combination, an improved recognition performance can be expected [18, 20]. A general overview and an introduction to the field of MCS is given in [9]. Several combination methods for character, numeral and word recognition have been proposed in the literature [7, 20, 23]. However, the combination of the outputs of multiple handwritten text line recognizers differs from standard multiple classifier combination, because the output of a text line recognizer is a sequence of word classes rather than just one single word and the number of words may differ between several recognizers. Therefore the recognizer output voting error reduction (ROVER) [4] framework is applied in this paper. To combine the output of the recognizers under this framework, the word sequences are incrementally aligned using a string matching algorithm. Then a voting strategy is applied to get the final result. A similar MCS approach based on hidden Markov models (HMMs) has been introduced recently [11]. While the approach in [11] combines only three recognizers, using just the number of occurrences in its voting strategy, more recognizers are combined in this paper and advanced voting strategies are proposed.

The rest of the paper is organized as follows. A description of all recognition systems for the combination experiments is given in Section 2, and the methodology for combining the different recognizers is introduced in Section 3. Section 4 presents the experiments and results, and finally, Section 5 draws some conclusions and gives an outlook to future work.

2 Recognition Systems

Thirty individual recognition systems are used for the combination described in this paper. They are based on three different feature sets. A total of ten BLSTM classifiers have been trained on each feature set.

2.1 Preprocessing and Feature Extraction

The first set of features uses off-line images generated from the on-line data [12]. The text line to be recognized is normalized with respect to skew, slant, writing width and baseline location. Normalization of the baseline location means that the body of the text line (the part which is located between the upper and lower baselines), the as-
cender part (located above the upper baseline), and the de-
scender part (below the lower baseline) will be vertically
scaled to a predefined size each. Writing width normali-
tion is performed by a horizontal scaling operation, and its
purpose is to scale the characters so that they have a pre-
defined average width. To extract the feature vectors from
the normalized images, a sliding window is used. The
width of the window is one pixel, and nine geometrical
features are computed at each window position. Thus an
input text line is converted into a sequence of feature vec-
tors in a 9-dimensional feature space. The following fea-
tures are computed: the average gray value of the pixels in
the window (1), their center of gravity (2), the second ord-
er moment in vertical direction (3), the positions (4,5) and
gradients (6,7) of the uppermost and lowermost black
pixel, the number of black-white transitions between the
uppermost and lowermost pixel in an image column (8),
and the proportion of black pixels to the number of pixels
between these two points (9).

To get the second set of features, the on-line data are
used directly. The individual text lines are corrected with
respect to their skew. For this purpose we perform a linear
regression through all points. For slant normalization, we
compute the histogram over all angles between the lines
connecting two successive points of the trajectory and the
horizontal line [8]. After normalization, delayed strokes, e.g.
the crossing of a “t” or the dot of an “i” are removed, using
simple heuristics. Next, we perform an equidistant resam-
ping of the point sequence, i.e. the original se-
quence of points is replaced by a sequence of points on the
trajectory where all consecutive points have the same dis-
tance to each other. The optimal value for the distance has
been empirically found. This step is needed because dif-
ferent writers write at a different speed. The next impor-
tant step is the computation of the baseline and the corpus
line. For this purpose, we compute two linear regressions
through the minima and maxima of the y-coordinates of
the strokes and remove the least fitting points. This cor-
rection step is done twice which results in the estimated
baseline (minima) and corpus line (maxima). The baseline
is subtracted from all y-coordinates to make them equal
to the x-axis. This step also gives us the three main writ-
ing areas. As the last preprocessing step, the width of
the characters is normalized. The extracted features are
the following: the pen-up/pen-down feature (1); the hat-
feature, which indicates if a delayed stroke has been re-
moved at the same horizontal position (2); the speed (3);
the normalized x- and y-coordinate (4,5); the writing di-
rection (6,7); the curvature (8,9); the vicinity aspect (10);
the vicinity slope (11,12); the vicinity curliness (13); the
vicinity linearity (14); the ascenders and descenders in the
off-line vicinity of the considered point (15,16); and the
context map, where the two-dimensional vicinity of the
point is transformed to a 3 x 3 map and the resulting nine
values are taken as features (17-25).

The third set of features is based on the same feature
extraction steps as used for the second feature set, up to
two differences. Before applying the normalization oper-
ations, an additional step is introduced, which is motivated
by the nature of the whiteboard data. The text lines on a
whiteboard usually have no uniform skew along the whole
line and the slant and size of the letters is not the same at
the beginning and at the end of a line. This is caused by the
fact that people stand, rather than sit, during writing and
the arm does not rest on a table. Therefore the text line is
split into subparts and the preprocessing is done for each
subpart separately. Splitting is done at gaps that are larger
than the mean gap size. Also the size of both subparts that
result from splitting has to be greater than a predefined
threshold. Slant correction is done for each subpart indi-
vidually. It is supplemented with the following steps. We
weight the angle histogram values with a Gaussian with
its mean at the vertical angle, and the variance empiri-
cally set. This is beneficial because some words are not
properly corrected if a single long straight line is drawn
in horizontal direction, which results in a large histogram
value. We also smooth each histogram entry with its di-
rect neighbors using the window (0.25, 0.5, 0.25), because
in some cases the correct slant is at the border of two an-
gle intervals and a single peak at another interval may be
slightly higher. This single peak will become smaller after
smoothing.

2.2 BLSTM combined with CTC

Recurrent neural networks (RNNs) [16] are a natu-
ral choice for on-line handwriting recognition, since they
are able to access extensive contextual information when
transcribing characters or words. Until recently however,
RNNs were limited to making separate classifications at
every timestep in an input sequence. This severely limited
their applicability to domains such as speech recognition
and cursive handwriting recognition, since it required that
the training data be pre-segmented, and that the network
outputs be post-processed to give the final transcriptions.

Connectionist temporal classification (CTC) [3] is an
RNN objective function designed to overcome the above
mentioned problem. It uses the network to define a prob-
ability distribution over a fixed set of labels plus an additional ‘blank’, or ‘no label’ unit. It then interprets the sequence of network outputs as a probability distribution over all possible transcriptions for a given input sequence, and trains the network by maximizing the log probabilities of the correct transcriptions on the training set.

As already mentioned, the advantage of RNNs derives from their ability to access contextual information. It is therefore important to choose an RNN architecture that maximizes the amount of context available.

Long short-term memory (LSTM) [6] is an RNN architecture specifically designed to bridge long time delays between relevant input and target events, making it very suitable for handwriting recognition, where long range context is required to disambiguate individual labels. An LSTM hidden layer consists of multiple recurrently connected subnets, known as memory blocks. Each block contains a set of internal units, or cells, whose activation is controlled by three multiplicative units: the input gate, forget gate and output gate. Figure 1 provides a detailed illustration of an LSTM memory block with a single cell. The cell has a recurrent connection with fixed weight 1.0. The three gates collect input from the rest of the network, and control the cell via multiplicative units (small circles). The activations of the input and output gates scale the input and output of the cell while that of the forget gate scales the recurrent connection of the cell. The cell input and output squashing functions (g and h) are applied at the indicated places.

Whereas standard RNNs make use of previous context only, bidirectional RNNs (BRNNs) [17] are able to incorporate context on both sides of every position in the input sequence. This is useful in handwriting recognition, since it is often necessary to look to both the right and left of a given letter in order to identify it. Figure 2 shows a comparison of a standard RNN and a BRNN in two time states. In the BRNN there exist two hidden layers, i.e. one layer for each direction, and the input/output neurons (marked with I/O) are connected to both.

Combining the above two concepts gives bidirectional LSTM (BLSTM). The recognition architecture used in this paper is based on BLSTM networks combined with CTC. CTC allows the network to be trained with unsegmented data. The intuition is that, because we don’t know where the labels within a particular transcription will occur, we sum over all the places where they could occur. In general, a large number of paths will correspond to the same label sequence, so a naive calculation of the conditional probability is unfeasible. However, it can be efficiently evaluated using a graph-based algorithm, similar to the forward-backward algorithm for HMMs, which is therefore called CTC forward-backward algorithm [3].

The number of hidden cells is fixed to 100. The only parameter that is optimized on the validation set is the number of training iterations. To obtain different classifiers for each feature set, the BLSTMs have been initialized randomly using a different random seed for each initialization.

### 3 Combination Methodology

Since the combination of the outputs of multiple handwritten text line recognizers differs from standard multiple classifier combination, the ROVER combination strategy has been chosen. This strategy consists of two stages. Because the recognizers output word sequences corresponding to whole text lines and because there may be a different number of words in each sequence, the output sequences are aligned into a word transition network (WTN) first. A voting strategy is then applied to select the best scoring word at each location for the final transcription.

Finding the optimal alignment for $n$ sequences is NP-complete [22]. Thus an approximate solution for the alignment is chosen. This solution aligns the multiple sequences incrementally by building WTNs. At the beginning, the first and the second word sequence are aligned in a single WTN, using the string matching algorithm described in [21]. The resulting WTN is aligned with the next word sequence giving a new WTN, which is then aligned with the next recognition result, and so on. This method does not guarantee an optimal solution, but in practice the suboptimal solutions often provide an alignment of sufficiently high accuracy. An example alignment...
of the output of three recognizers (denoted by $W_1$, $W_2$, and $W_3$) is shown in Fig. 3. The columns in the WTNs denote correspondence sets (sets of corresponding words) that are identified by the alignment process. Note that the symbol $\epsilon$ marks null-transitions, i.e., transitions where an empty string is chosen as an alternative.

After alignment a voting module extracts the best scoring word sequence from the WTN. One possibility is to take only the number of occurrences of a word $w$ for making a decision. In case of ties, the output of the best performing system on the validation set is taken. In the example of Fig. 3 it would be the “In” from $W_1$ which yields the final output “In mid-april Anglesey”. Note that this is the correct transcription, which is not present in the recognition results of any single recognizer.

In addition to the frequency of occurrence, the confidence of the recognizers can be taken into account. The trade off between the frequency of occurrence and the confidence score is weighted with a parameter $\alpha$. Let $c$ be a correspondence set of the WTN containing $n$ word classes $w_1, \ldots, w_n$. The number of occurrences of each word class $w_i$ is denoted by $N_i$. Then the score $S(w_i)$ of a word $w_i$ is:

$$S(w_i) = \alpha \cdot \frac{N_i}{\sum_{j=1}^{n} N_j} + (1 - \alpha) \cdot C(w_i),$$

(1)

where $C(w_i)$ is the combined confidence score of word class $w_i$. There exist several methods to calculate $C(w_i)$. First, the average of all confidence scores of the occurrences of word class $w_i$ can be used. Second, the maximum of these confidence scores may be chosen. Setting $\alpha = 1$ results in a voting that takes only the number of occurrences into account.

Another parameter needed in the combination is the confidence score of the null-transition $C(\epsilon)$. It determines how often the null-transition is taken instead of another word class. If no null-transition is taken, i.e., $C(\epsilon)$ is very low, the output transcription tends to be longer and more insertion errors occur. On the contrary, if $C(\epsilon)$ is too large, more deletions occur. The two parameters $\alpha$ and $C(\epsilon)$ are optimized on a validation set in this paper.

## 4 Experiments and Results

The experiments have been performed on the IAM-OnDB [10], a large on-line handwriting database acquired from a whiteboard. It consists of 13,040 written lines, containing 86,272 instances of 11,050 distinct words. For the alignment and construction of the WTN, the Rover tool from the National Institute of Standards and Technology (NIST) implementing the ROVER framework [4] has been used.

The IAM-OnDB-t2 benchmark task has been used for the experiments. The benchmark data is divided into four sets, one set for training the models, two sets for validating meta parameters, and one independent test set for measuring the final recognition results. The vocabulary contains the 20,000 most frequent words out of three corpora (LOB Corpus, Brown Corpus, Wellington Corpus). The parameters for the recognition and the combination have been optimized on the first validation set. A bigram language model is included in the experiments. This language model has been optimized on the second validation set. The language model training is based on three different corpora (LOB Corpus, Brown Corpus, Wellington Corpus). To guarantee that the test data is not used for training, the texts of the IAM-OnDB have been removed from the LOB Corpus. The performance of the classifiers is measured on the word level accuracy in all our experiments.

A summary of the performance of the individual recognition systems on the test set is given in Table 1. Altogether 30 classifiers are involved in the experiments, i.e. 10 classifiers for each feature set. The different feature sets are denoted by “off-line (1)” for off-line features, “on-line (2)” for on-line features, and “on-line (3)” for on-line features extracted after the refined preprocessing. The accuracy of the best performing classifier for each feature set is given in the right column. Additionally, the average accuracy of the ten classifiers is given in brackets. The best neural network classifier has been trained without the refined preprocessing (“on-line (2)”). It performs at 81.26 %, which is 0.19 % higher than the best CTC with refined preprocessing (“on-line (3)”). However, this maximum performance is perhaps an outlier, since the average accuracy of the “on-line (3)” CTC is 80.1 %, compared to 79.8 % of the “on-line (2)” CTC. The off-line CTC systems perform with an average accuracy of 73.6 %.

Several parameters of the MCS have to be optimized during validation. First, there are the parameters for vot-

### Table 1. Recognizers used for the combination experiments

<table>
<thead>
<tr>
<th>System</th>
<th>Best accuracy (average)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTC off-line (1)</td>
<td>76.43 % (73.6 %)</td>
</tr>
<tr>
<td>on-line (2)</td>
<td>81.26 % (79.8 %)</td>
</tr>
<tr>
<td>on-line (3)</td>
<td>81.07 % (80.1 %)</td>
</tr>
</tbody>
</table>

![Accuracy in %](image)
Table 2. Results of the selected combinations on the validation set

<table>
<thead>
<tr>
<th>System</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Best individual classifier</td>
<td>74.63 %</td>
</tr>
<tr>
<td>Three classifiers</td>
<td>77.03 %</td>
</tr>
<tr>
<td>Optimized weighting</td>
<td>77.20 %</td>
</tr>
<tr>
<td>Optimized mix</td>
<td>80.40 %</td>
</tr>
</tbody>
</table>

The accuracy of each feature set has been varied from one to ten, e.g. if the feature set of the recognizers needs to represent a confidence measure, $C(w_i)$ see (1). The performance on the validation set has been used as confidence score $C(w_i)$ for each of the classifiers. The final voting strategy consists in taking the maximum rather than the average of the individual confidence scores in (1), because it returned better recognition results in all experiments on the validation set.

The parameters for voting, $\alpha$ and $C(\epsilon)$, are optimized on the validation set. Before voting can be applied, the outputs of the recognizers need to represent a confidence measure, $C(w_i)$ see (1). The performance on the validation set has been used as confidence score $C(w_i)$ for each of the classifiers. The final voting strategy consists in taking the maximum rather than the average of the individual confidence scores in (1), because it returned better recognition results in all experiments on the validation set.

Figure 4 illustrates the accuracy on the validation set for different parameter combinations for an example classifier ensemble. It is observed that the values do not change significantly for $\alpha > 0.8$. The highest accuracy in this example is reached at $\alpha = 0.5, C(\epsilon) = 0.7$.

The order of the classifiers has an influence on the alignment, for only a suboptimal alignment strategy is chosen. A commonly used strategy begins with the best classifier on the validation set and sequentially adds the next best classifier. This strategy has been adopted in this paper.

To get the number of individual classifiers to be included in the ensemble, we investigated several strategies. First, only the best classifier for each feature set has been selected, resulting in an ensemble of three classifiers (second row in Table 2). This ensemble has a higher recognition accuracy on the validation set than the best single classifier (first row in Table 2). Second, the weighing of these classifiers has been optimized using weights from 0 to 1 with a step size of 0.1. The best weights are 0.6 for “off-line (1)”, 0.5 for “on-line (2)”, and 0.5 for “on-line (3)”. However, there is only a little performance increase on the validation set (third row in Table 2). Finally, the number $n_c (c = 1, 2, 3)$ of individual classifiers from each feature set has been varied from one to ten, e.g. if $n_1 = 3$, the three best “off-line (1)” systems are used. This results in $10^3$ combinations that have been tested on the validation set. The results on the validation set show a promising increase of the recognition accuracy (last row in Table 2). The optimized ensemble of classifiers uses six “off-line (1)” systems, one “on-line (2)” system, and six “on-line (3)” systems.

The final results on the test set appear in Table 3. The optimized combination performs statistically significantly better than the best individual classifier at a significance level of 1%. The recognition accuracy is 83.64 %, corresponding to error reduction of more than 12%.

Table 3. Results on the test set

<table>
<thead>
<tr>
<th>System</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Best individual classifier</td>
<td>81.26 %</td>
</tr>
<tr>
<td>Three classifiers</td>
<td>81.27 %</td>
</tr>
<tr>
<td>Optimized weighting</td>
<td>81.18 %</td>
</tr>
<tr>
<td>Optimized mix</td>
<td>83.64 %</td>
</tr>
</tbody>
</table>

Table 3 also shows the performance of the combination of the best individual classifiers for each feature set (second row). Surprisingly, the recognition accuracy drops from 81.27 % to 81.18 % if the optimal weights found on the validation set are used for weighting the classifiers. This confirms the observation during validation that the weighting does not lead to a large difference in performance. Note that the performance on the test set is higher than on the validation set. This has already been observed in previous works [11]. The main reason for this observation seems to be that the tests set contains data that is easier to recognize.

5 Conclusions

In this paper a multiple classifier system (MCS) for the recognition of handwritten notes written on a whiteboard has been presented. While several MCS for character, numeral and word recognition have been proposed, only few methods exist for the combination of complete text lines, because the output of a text line recognizer is a sequence of word classes rather than just one single word and the number of words may differ between several recognizers. Therefore the ROVER framework has been used to combine the output sequences of the recognizers. This framework first aligns the word sequences incrementally in a word transition network, and then, at each output position, applies a voting strategy to select the final result.

The experiments have been performed on the IAM-OnDB-t2 benchmark. Several BLSTM recognizers have been combined. For the experiments a language model is included, which has been trained on the second validation set, while the first validation set has been used to optimize the individual systems and the combination parameters. The experimental results on the test set show a highly significant improvement of the recognition performance. The final recognition accuracy is 83.64 %, corresponding to an error reduction of more than 12 % compared to the best individual classifier.

An interesting outcome of our experiments is that applying an MCS using only three classifiers did not increase the performance significantly, even if the weighting is optimized. It can be concluded that simply applying an MCS is not helpful in all cases. However, using different recognizers by changing the initialization of the network leads to better recognition rates.

While we already achieved a performance increase, there are still possibilities to further improve the system in future work. This can be done by using more elaborated confidence scores. For example, the word-level confidences of the individual classifiers or other confidence measures proposed in the literature [1, 5, 14] could be taken.
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