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SpottingNet: Learning the Similarity of Word Images with Convolutional Neural Network for Word Spotting in Handwritten Historical Documents

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***Abstract*—Word spotting is a content-based retrieval process that obtains a ranked list of word image candidates similar to the query word in digital document images. In this paper, we present a convolutional neural network (CNN) based end-to-end approach for Query-by-Example (QBE) word spotting in handwritten historical documents. The presented models enable conjointly learning the representative word image descriptors and evaluating the similarity measure between word descriptors directly from the word image, which are the two crucial factors in this task. We propose a similarity score fusion method integrated with hybrid deep-learning classification and regression models to enhance word spotting performance. In addition, we present a sample generation method using location jitter to balance similar and dissimilar image pairs and enlarge the dataset. Experiments are conducted on the George Washington (GW) dataset without involving any recognition methods or prior word category information. Our experiments show that the proposed model yields a new state-of-the-art mean average precision (mAP) of 80.03%, significantly outperforming previous results.**

Keywords-component; word spotting; similarit learning; similarity score fusion; convolutional neural network

I. INTRODUCTION

With the increased demand for text understanding and semantic analysis in document images and the lack of reliable and robust optical character recognition (OCR) for specific languages, symbols or low quality images, word spotting has attracted considerable attention from the document analysis community. The goal of word spotting is to search an ordered list of word image candidates similar to the queried word in the entire image dataset during the content-based retrieval procedure. According to the different representations of the query word, there are two main approaches to word spotting, namely, Query-by-String (QBS) [4] and Query-by-Example (QBE) [1]. If the query word is represented as an arbitrary text sequence, the technique used is QBS; alternatively, if an image of the queried word exists in the document, QBE is used.

In this work, we focus on QBE and assume that an annotated location of the word in the document images is supplied; thus, we apply the cropped word image directly without involving text localization and segmentation. That is, we mainly address the content-based retrieval process. The two key challenges of QBE word spotting are the representation of word images and the similarity measure between word image representations. Most popular algorithms are based on applying projection profiles [2][3], word geometry information [2][3], statistical features [7], SIFT [6][9], or other hand-crafted features to generate fixed or variable length feature sequences for word image descriptors, while using Dynamic Time Warping (DTW) [2][3][5][6], Hidden Markov Models (HMMs) [6][7] and BLSTM [4][8] to measure the relevance of the word feature representations; and achieved promising results on different word spotting benchmarks.

However, effectively spotting words in image-based documents, especially handwritten or historical documents, poses a great challenge owing to the large variability and confusion of handwritten manuscripts or the low quality of historical images, resulting in inadequate performance of previous research. For example, the state-of-the-art mean average precision (mAP) of a widely used historical handwritten dataset, known as the George Washington (GW) dataset [2], is about 62.72% [9] in the case where recognition methods and prior word category information are not accessible in the literature.

Conversely, with the increased development of deep learning algorithms in recent years, convolutional neural networks (CNN) [10] have enabled a breakthrough in many computer vision tasks [11-16]. Many research studies have subsequently applied CNNs to learn the similarity of two input image patches. Zbontar and Lecun [17] proposed CNN-based methods to learn the similarity of image patches for a stereo matching problem and showed improved performance results on the KITTI datasets. Hu et al. [19] presented a discriminative deep metric learning method using a CNN for face verification in the wild and achieved very promising performance on the LFW and YFT datasets. Zagoruyko et al. [18] applied several different CNN architectures to compare image patches as well as encode a general similarity function and attained the best results on several local image patch benchmarks.

In this paper, we propose a similarity score fusion method based on a deeply trained classification and regression model in a complementary, facilitative and optimized manner. Our designed models can learn the word descriptors and similarity score between word descriptors directly from a

cropped word image thanks to the CNN's outstanding end-to-end mechanism. Moreover, through the presented location jitter sample generation approach, we can construct a balanced and sufficiently large dataset with positive (similar) image pairs and negative (dissimilar) image pairs of word images to overcome data imbalance problem. Inspired by [18], we design different traditional CNN architectures, including 2-channel, Siamese, and pseudo-Siamese networks to investigate the similarity learning performance of diverse models.

The remainder of this paper is set out as follows. Section 2 gives a detailed introduction to our approaches, while Section 3 presents our experimental results and an analysis thereof. Finally, the conclusion is given in Section 4.

II. METHODOLOGY

A. Learning optimization

It is noted that we can consider the similarity comparison of two word images as a classification as well as a regression problem by collecting a dataset with positive and negative word image pairs using supervised learning. For the classifier, we can obtain a 2-dimensional label distribution, while for the regressor, a 1-dimensional similarity score ranging from 0 to 1 can be acquired directly. Suppose we have $K = 2$ categories and the training data for each category are denoted as $(x^{(n)}, y^{(n)})$, $n = \{1, \dots, N\}$, where $x^{(n)} \in \mathbb{R}^D$ and $y^{(n)} \in \{0, 1\}$ are the feature vector and label, respectively. Specifically, $y^{(n)} = 1$ means it is a similar image pair, and zero denotes a dissimilar pair. In addition, θ is represented as the model parameters, and λ as the weight decay for regularization.

1) Classification model: With the development of deep learning algorithms, using the softmax loss function for classification problems [12] has become popular. The loss is described as:

$$\min_{\theta} \frac{\lambda}{2}\|\theta\|_2 - \frac{1}{N}\left\{\sum_{n=1}^{N}\sum_{k=1}^{K} 1\{y^{(n)} = k\} \log \frac{e^{\theta_k^T x^{(n)}}}{\sum_{l=1}^{K} e^{\theta_l^T x^{(n)}}}\right\}, \tag{1}$$

where $\sum_{l=1}^{K} e^{\theta_l^T x^{(n)}}$ is a factor of normalization, and $1\{\cdot\}$ is the indicator function defined as following:

$$1\{y^{(n)} = k\} = \begin{cases} 1 & y^{(n)} = k \\ 0 & y^{(n)} \neq k \end{cases}. \tag{2}$$

Furthermore, as hinge loss function is also widely used for binary classification, hence we intend to evaluate the performance of the same model with an embedded corresponding loss function for optimization. The hinge loss function is given by Eq. (3).

$$\min_{\theta} \frac{\lambda}{2}\|\theta\|_2 + \frac{1}{N}\left\{\sum_{n=1}^{N}\sum_{k=1}^{K} \max(0, 1 - \delta\{y^{(n)} = k\} \cdot \theta_k^T x^{(n)})\right\}, \tag{3}$$

where $\delta\{\cdot\}$ is given as:

$$\delta\{y^{(n)} = k\} = \begin{cases} 1 & y^{(n)} = k \\ 0 & y^{(n)} \neq k \end{cases}. \tag{4}$$

The loss functions defined in Eq. (1) and (3) can be minimized by the stochastic gradient descent algorithm during the training process.

2) Regression model: For the regression model, we use the binary cross-entropy loss for training and obtain a similarity value mapped onto the range [0, 1] by the sigmoid function. The loss is given:

$$\min_{\theta} \frac{\lambda}{2}\|\theta\|_2 - \frac{1}{N}\left\{\sum_{n=1}^{N} y^{(n)} \log(\mathrm{P}_n) + (1 - y^{(n)}) \log(1 - \mathrm{P}_n)\right\}, \tag{5}$$

where P_n is defined as $P_n = 1/1 + e^{-\theta^T x^{(n)}}$. The output of the model is expected to be closed to the target label.

3) Similarity score fusion method: As previously mentioned, the similarity measure for word image pairs can be regarded as a classification and a regression problem, and thus we assume that these two model types can be combined to improve the performance in a joint and complementary manner. In this section, we explain the similarity score fusion method based on a deep learning classifier and regressor model. Suppose S_{cls} and S_{reg} are the similarity confidence scores obtained from the classifier and regressor model, respectively. The classifier obviously provides a 2-dimensional class distribution, and S_{cls} can be computed in terms of probability normalization as:

$$S_{cls} = \frac{e^{\theta_K^T x^{(n)}}}{\sum_{l=1}^{K} e^{\theta_l^T x^{(n)}}}. \tag{6}$$

The regressor outputs 1-dimesional similarity score directly and we map it onto the range [0, 1] via a sigmoid function. Thus, S_{reg} is denoted as:

$$S_{reg} = \frac{1}{1 + e^{-\theta^T x^{(n)}}}. \tag{7}$$

Moreover, the fusion similarity score S_{fuse} is denoted as:

$$S_{fuse} = F(S_{cls}, S_{reg}), \tag{8}$$

where $F(\cdot)$ is the fusion function and S_{cls}, S_{reg} is the input for $F(\cdot)$.

Our experiments in next section will show that our proposed score fusion method yields a better mAP result than using only single classification or regression model. An overview of similarity score fusion is illustrated in Fig. 1.

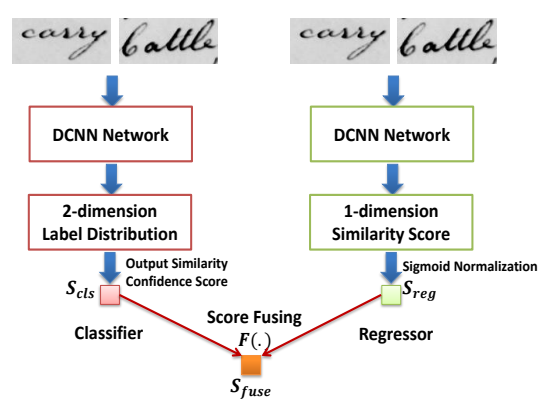

Figure 1. Score fusion method based on deep-learning classifier and regressor models.

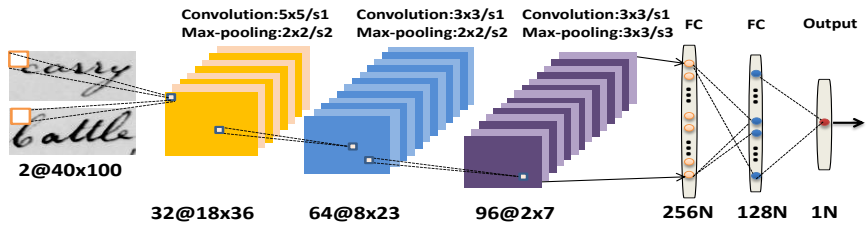

Figure 2. Illustration of 2-channel regression network model.

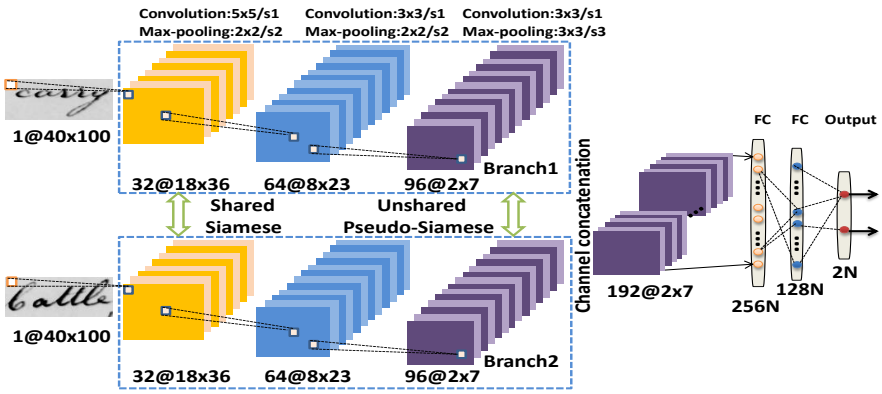

Figure 3. Overview of Siamese and pseudo-Siamese classification network models.

B. *Location jitter for data augmentation*

There are not nearly as many positive pairs as negative pairs, which may result in data imbalance and incorrect network guidance. For instance, suppose there are words from K classes with N images per class $(K \gg N)$. In this case, we can collect $N_{pos} = K \cdot C_N^2 = K\frac{N(N-1)}{2}$ positive image pairs, and $N_{neg} = K \cdot (K-1) \cdot N^2$ negative pairs, which easily leads to the conclusion that $N_{pos} \propto KN^2$, $N_{neg} \propto K^2N^2$. Under the condition $K \gg N$, it is obvious that N_{neg} is much greater than N_{pos}. Therefore, it is necessary to artificially enlarge the dataset by a label-preserving transformation to keep the data balanced. In this work, we present a random location jitter approach to augment the data and retain the word content information integrity as far as possible, which is crucial to word image similarity learning. The proposed sample generation method is described below:

- Given an original word image of size $H \times W$, calculate its center point coordinate $C_{origin}(x, y)$. Denote $C_{target}(x', y')$ as the jittered target center point coordinate;
- Define $x' \sim U[x - S_x, x + S_x]$ and $y' \sim U[y - S_y, y + S_y]$, where U denotes the union distribution, S_x and S_y represent the jitter scope on the x- and y-axes, respectively, and with $S_x = S_y = 5$ used in practice. Sample x' and y' to obtain $C_{target}(x', y')$;
- Apply $C_{target}(x', y')$ as the central anchor to crop the image patch of size $H \times W$.

In this way, several jitter-generated samples for each original word image can be obtained. Using this data augmentation operation, we can greatly increase the number of positive pairs and then randomly select an equal number of negative pairs to keep the data balanced.

C. *Network models*

Inspired by [18], we use the following three fundamental CNN models to compare the similarity of two cropped word images, as well as to evaluate the trade-off between flexibility and performance, while taking into consideration the efficiency of the different models.

Siamese network [20][21] is divided into two dependent branches with each branch sharing parameters in every weighted layer. Each branch takes one of image pair as input and proceeds to feature extraction via a series of convolutional and sub-pooling layers synchronously. The equal-size feature maps extracted from each branch are concatenated across the channel and then connected to the decision network (classification or regression network) to calculate the similarity measure of this word image pair.

Pseudo-siamese network resembles the Siamese net-work, but differs in that its two branches are independent without shared parameters. This increases the number of parameters, while improving the flexibility of the network architecture for each branch.

2-channel network applies an image pair as a 2-channel input image array, with the channels jointly convolved in the first convolutional layer. This is the most flexible and fastest of the three network models with respect to the training process. The three network model architectures designed are depicted in Figs. 2 and 3.

III. EXPERIMENTS AND ANALYSIS

A. Experimental data

The GW dataset [2] is a collection of 20 pages of letters and 4860 words annotated at word level written by George Washington and his assistants. The dataset was split randomly into 15 pages for training and the remaining five pages for testing, so a certain category of word, which may exist in the testing set, is not likely to appear in the training set. Having evaluated the aspect ratio (height/width) and width distribution (width is more important for the word image itself) of the dataset, we decided to normalize the word images to size 40×100. Standard mAP was used as the evaluation method.

B. Implementation details

We trained our proposed classification and regression model from scratch via back-propagation and stochastic gradient descent (SGD) in an end-to-end manner. All the weights of the new layers were initialized with a zero mean and a standard deviation of 0.01 Gaussian distribution. The base learning rate was 0.01 and divided by 10 for each 50K mini-batch until convergence. We use a momentum of 0.9 and weight decay of 0.0002. Our experiments were carried out on the popular CNN platform, Caffe [22], using a GTX TITAN BLACK GPU card. Furthermore, for the similarity score fusion function S_{fuse}, we simply set S_{fuse} as: $S_{fuse} = F(S_{cls}, S_{reg}) = (S_{cls} + S_{reg})/2$ in practice after empirically observation.

C. Evaluation of three classification models embedded corresonding binary loss function for optimization

In this section, we compare the performance of the proposed three fundamental classification models with an embedded corresponding loss function on the five-page testing dataset over five runs using the same training details and strategies. The results are given in Table 1. It is generally seen that the 2-channel network is superior to the other two models and the softmax loss function is better suited to this similarity learning task. The best mean mAP and standard error (%) performance of the 2-channel model with softmax loss function is 78.46±0.18.

D. Analysis of similarity score fusion approach

An important finding from our experiments is that the 2-channel network precedes the other model architecture. Thus, when considering this similarity learning task as a regression problem, we also trained a 2-channel CNN-based regression model with embedded binary cross-entropy loss for optimizing from scratch to obtain a 1-dimensional similarity score. In this way, we obtained an average mAP and standard error (%) of 77.51±0.27. As mentioned above, the mAP rate of the proposed 2-channel classification model with softmax loss function for training is 78.46±0.18. In this section, we evaluate these two models ensemble performance using the proposed similarity score fusion method. The corresponding experiments are denoted as 2-ch-cls, 2-ch-reg, and 2-ch-cls+2-ch-reg, respectively. Figure 5 shows the results of the three experiments over five runs. It can be seen that our score fusion method yields a better mAP result than using only a single classifier or regressor model with the best mAP of 80.03%.

Table 1 Comparison of three network models with coresponding loss function in terms of mAP for five runs.

Model+loss function	Mean mAP and standard error(%)
2-channel+softmax loss	**78.46±0.18**
2-channel+hinge loss	72.40±0.11
Siamese+softmax loss	77.88±0.26
Siamese+hinge loss	70.40±0.07
Pseudo-Siamese+ softmax loss	67.17±0.23
Pseudo-Siamese+ hinge loss	62.13±0.15

E. Comparison with different methods on GW dataset

To further evaluate our proposed approaches, we compared the performance of different QBE word spotting methods on the GW dataset without involving recognition methods or any word category prior information. The compared methods include DTW [5], SC-HMM [5], BoVW+Cosine Distance [6], and SIFT+FV [9] with the results given in Table 2. It is worth noting that not all the results are directly comparable because the training and testing dataset partitions are not official and may differ from each other. However, the published results in the literature provide an evaluable measure of the proposed ideas in the expected scope. In the table, we can see that our 2-ch-cls or 2-ch-cls+2-ch-reg model outperforms previous state-of-the-art results with a 15%–38% improvement in mAP. To the best of our knowledge, this is the first time CNN-based methods have been applied to learn the similarity of two word image patches for QBE word spotting. The qualitative results for word spotting on the GW dataset are shown in Fig. 6.

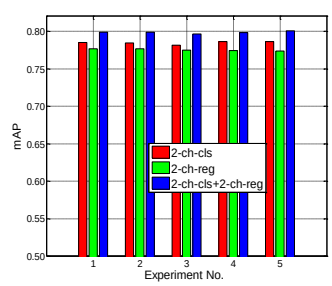

Fig. 5. mAP results of similarity score fusion method over five runs.

Table 2 mAP of our proposed techniques and reported methods using the GW for word spotting

Methods	mAP(%)
BoVW+Cosine Distance [6]	42.20
DTW [5]	50.00
SC-HMM [5]	53.10
SIFT+FV [9]	62.72
Proposed 2-ch-cls	78.46
Proposed 2-ch-cls+2-ch-reg	**80.03**

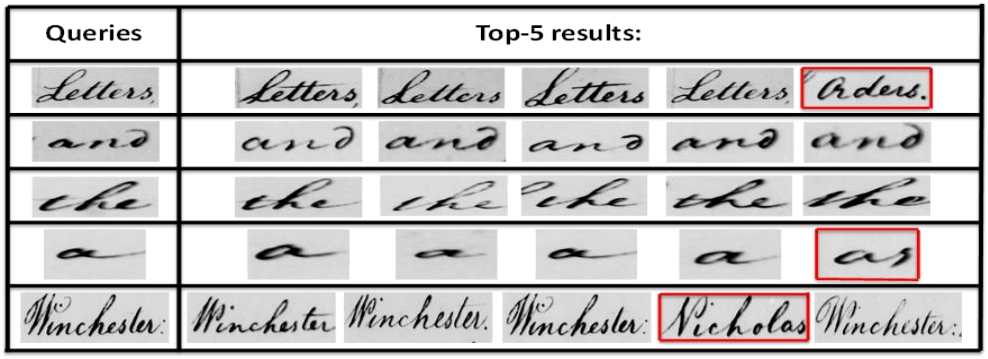

Figure 6. Qualitative results of word spotting on the GW. Irrelevant words to the query are outlined in red.

IV. Conclusion and Discussion

In this paper, we presented a CNN based end-to-end approach for QBE word spotting in historical handwritten documents. A new similarity score fusion method based on a deep-learning classification model and regression model was proposed to achieve better retrieval performance. Furthermore, we presented a location jitter sample generation method that retains the maximum word content information, to construct a balanced and sufficiently large image pair dataset. In addition, we explored three different CNN architectures embedding two common loss functions for classification. We showed that the 2-channel network is superior to both the Siamese and pseudo-Siamese networks while the softmax loss function is better suited to this task. Using the proposed score fusion method, we achieved improved mAP performance in a complementarily optimized way. The best mAP rate we obtained is 80.03% on the GW dataset, which is a significant improvement over previous approaches

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