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Offline Writer Identification Using Convolutional Neural Network Activation Features

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Abstract. Convolutional neural networks (CNNs) have recently become the state-of-the-art tool for large-scale image classification. In this work we propose the use of activation features from CNNs as local descriptors for writer identification. A global descriptor is then formed by means of GMM supervector encoding, which is further improved by normalization with the KL-Kernel. We evaluate our method on two publicly available datasets: the ICDAR 2013 benchmark database and the CVL dataset. While we perform comparably to the state of the art on CVL, our proposed method yields about 0.21 absolute improvement in terms of mAP on the challenging bilingual ICDAR dataset.

1 Introduction

In contrast to physiological biometric identifiers like fingerprints or iris scans, handwriting can be seen as a behavioral identifier [31]. It is influenced by factors like schooling or aging. Finding an individual writer in a large data corpus is formally defined as *writer identification*. Typical applications lie in the fields of forensics or security. However, writer identification recently also raised interest in the analysis of historical texts [3,10].

The task can be categorized into a) *online* writer identification, for which temporal information of the text formation can be used, and b) *offline* writer identification which relies solely on the handwritten text. The latter can be further categorized into *allograph*-based and *textural*-based methods [4]. Allograph-based methods rely on local descriptors computed from small letter parts (allographs). Subsequently, a global document descriptor is computed by means of statistics using a pretrained vocabulary [5,9,10,15,28]. In contrast, textural-based methods rely on global statistics computed from the handwritten text, e. g., the ink width or angle distribution [3,8,12,28,21]. Both methods can be combined to form a stronger global descriptor [4,25,29].

In this work we propose an allograph-based method for offline writer identification. In contrast to expert-designed features like SIFT, we use activation features learned by a convolutional neural network (CNN). This has the advantage of obtaining features guided by the data. In each additional CNN layer the script is indirectly analyzed on a higher level of abstraction. CNNs have been widely used in image retrieval and object classification, and are among the top contenders on

challenges like the Pascal-VOC or ImageNet [19]. However, to the best of our knowledge CNNs have not been used for writer identification so far. A reason might be that typically the training and test sets of current writer identification datasets are disjoint making it impossible to train a CNN for classification. Thus, we propose to use CNNs not for the classification task but to learn local activation features. Subsequently, the local descriptors are encoded to form global feature vectors by means of GMM supervector encoding [5]. We also propose to use the Kullback-Leibler kernel, instead of the Hellinger kernel, on top of mean-only adapted GMM parameters. We show that this combination of activation features and encoding method performs at least as well as the current state of the art on two public datasets ICDAR13 and CVL.

2 Related Work

Allograph-based methods rely on a dictionary trained from local descriptors. This dictionary is subsequently used to collect statistics from the local descriptors of the query document. These statistics are then aggregated to form the global descriptor that is used to classify the document. Jain and Doerman proposed the use of vector quantization [14] as encoding method. More recent work concentrates on using Fisher vectors for aggregation [9,15]. While Fiel and Sablatnig [9] propose to use solely SIFT descriptors as the local descriptor, Jain and Doermann [15] suggest to fuse multiple Fisher vectors computed from different descriptors. In contrast, we will rely on the findings of Christlein et al. [5]. They showed that a very well known approach in speaker recognition, namely GMM supervector encoding, performs better than both Fisher vectors and VLAD encoding.

CNNs have been widely used in the field of image classification and object recognition. In the ImageNet Large Scale Visual Recognition Challenge for example, CNNs are among the top contenders [19]. In document analysis, CNNs have been used for word spotting by Jaderberg et al. [13], and for handwritten text recognition by Bluche et al. [2]. However, to the best of our knowledge, they have not been used in the context of writer identification.

Compared to regular feed forward neural networks, convolutional neural networks have fewer parameters that need to be trained due to sharing the weights of their filters across the whole input patch. This makes them easier to train, while not sacrificing classification performance for a smaller sized network. Instead of using a CNN for direct classification, one can choose to use a CNN to extract local features by interpreting the activations of the last hidden layer as the feature vector. Bluche et al. [2] propose to use features learned by a CNN for word recognition in conjunction with HMMs, and show that the learned features outperform previous representations. Gong et al. [11] employ a similar approach for image classification. Their local activation features are computed by calculating the activation of a pretrained CNN on the image itself, and on patches of various scales extracted from the image. The activations for each scale are then aggregated using VLAD encoding. The final image descriptor is formed by concatenating the resulting feature vectors from each scale.

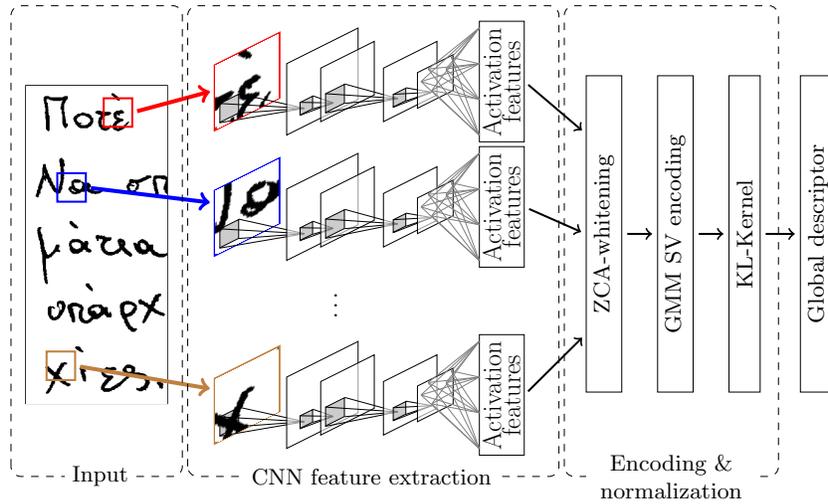


Fig. 1: Overview of the encoding process. The two main steps are the feature extraction using a pretrained CNN, and the encoding step, where the local features are aggregated using a pretrained GMM.

3 Writer Identification Pipeline

Our proposed pipeline (cf. Figure 1) consists of three main steps: the feature extraction from image patches using a CNN; the aggregation of all the local features from one document into one global descriptor; and the successive normalization of this descriptor. A pretrained CNN and a pretrained GMM are required for feature extraction and encoding, respectively.

3.1 Convolutional Neural Networks

In our pipeline the CNN is only used to calculate a feature representation of a small image patch, but not for directly identifying the writer. The training of the CNN, however, has to be performed by backpropagation, which requires labels for the individual patches. Therefore, during the training phase, the last layer of our network consists of 100 SoftMax nodes, representing the writer IDs of the ICDAR13 training set. After the training, this last layer is discarded and the remaining layers are used to generate the feature representation for the image patches. The architecture of the CNN we use is shown in Figure 2, where the dashed box marks the part of the CNN that is kept after the training procedure.

The CNN consists of 6 layers in total. The first layer is a convolutional layer, followed by a pooling layer. In the convolutional layer, the input patch is convolved with 16 filters. The pooling layer is then used to reduce the dimensions of the filter responses by performing a max pooling over regions of size 2×2 or 3×3 . The two subsequent layers follow the same principle: a convolutional layer

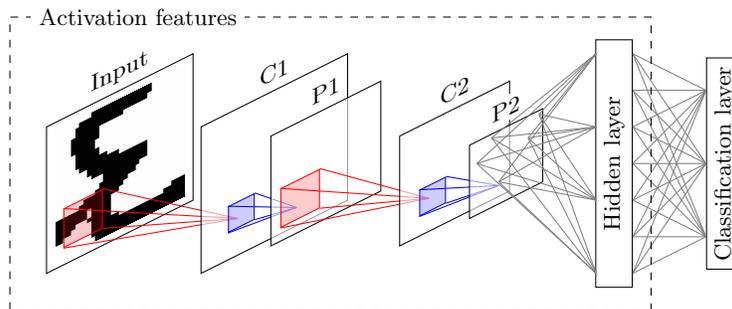


Fig. 2: Schematic representation of the used CNN. C1 and C2 are convolutional layers (red connections). P1 and P2 are max pooling layers (blue connections). The last three layers are fully connected (gray connections). After training only the part of the net inside the dashed box (activation features) is kept. The activations of the hidden layer become the local descriptor for the image patch.

with 256 filters is followed by a pooling layer. These first four layers constitute the convolutional part of the network. The output of the second pooling layer is next transformed into a 1-D vector which is fed into a layer of hidden nodes. For all of these layers rectified linear units (ReLU) are used as nodes. The last layer then consists of 100 nodes with a SoftMax activation function. They are used for classification during the training.

The training set consists of patches extracted from the ICDAR13 training set that are centered on the contour of the writing. For each of the 100 writers, ICDAR13 contains four images, two of Greek handwritten text and two of English handwritten text. We further divided this set into a training and test set, by using patches from the first English and Greek text for training, and patches from the second English and Greek text for testing the trained convolutional network. The training and test set consist independently of 4 million image patches of size 32×32 . The image patches are not preprocessed in any manner.

The training is performed by using the CUDA capabilities of the neural network library Torch [6]. All the CNNs are trained using the Torch implementation of stochastic gradient descent (SGD) with a learning rate of 0.01 for 20 epochs. For the first five epochs of training a Nesterov momentum $m = 0.9$ is used to speed up the training process.

3.2 GMM Supervector Encoding

Given the local activation features, we need to aggregate them to form one global descriptor for each document. For this task we use a variant of the GMM supervector approach of Christlein et al. [5].

In the training step a Gaussian mixture model (GMM) is trained as the dictionary from a set of ZCA-whitened activation features. This dictionary is subsequently used to encode the local descriptors by calculating their statistics

with regard to the dictionary. The K -component GMM is denoted by $\lambda = \{w_k, \boldsymbol{\mu}_k, \boldsymbol{\Sigma}_k | k = 1, \dots, K\}$, where w_k , $\boldsymbol{\mu}_k$ and $\boldsymbol{\Sigma}_k$ are the mixture weight, mean vector and diagonal covariance matrix for mixture k , respectively. The parameters λ are estimated with the expectation-maximization (EM) algorithm [7].

Given the pretrained GMM and one document, the parameters λ are first adapted to all activation features extracted from the document by means of a maximum-a-posteriori (MAP) step. Using a data-dependent mixing coefficient they are coupled with the parameters of the pretrained GMM. This leads to different mixtures being adapted depending on the current set of activation features [23]. Given the descriptors $\mathbf{X} = \{\mathbf{x}_t, \mathbf{x}_t \in \mathcal{R}^D, t = 1, \dots, T\}$ of a document, first the posterior probabilities $\gamma_t(k)$ for each \mathbf{x}_t and Gaussian mixture $g_k(\mathbf{x})$ are computed as:

$$\gamma_t(k) = \frac{w_k g_k(\mathbf{x}_t)}{\sum_{j=1}^K w_j g_j(\mathbf{x}_t)}. \quad (1)$$

Since the covariances and weights give only a slight improvement in accuracy [5], we chose to adapt only the means of the mixtures, thus, reducing the size of the output supervector and lowering the computational effort. The first order statistics are computed as:

$$\hat{\boldsymbol{\mu}}_k = \frac{1}{n_k} \sum_{i=1}^T \gamma_t(k) \mathbf{x}_t, \quad (2)$$

where $n_k = \sum_{t=1}^T \gamma_t(k)$. Then, these new means are mixed with the original GMM means:

$$\tilde{\boldsymbol{\mu}}_k = \alpha_k \hat{\boldsymbol{\mu}}_k + (1 - \alpha_k) \boldsymbol{\mu}_k, \quad (3)$$

where α_k denotes a data dependent adaptation coefficient. It is computed by $\alpha_k = \frac{n_k}{n_k + \tau}$, where τ is a relevance factor. The new parameters of the mixed GMM are then concatenated forming the GMM supervector: $\mathbf{s} = (\tilde{\boldsymbol{\mu}}_1^\top, \dots, \tilde{\boldsymbol{\mu}}_K^\top)^\top$. This global descriptor \mathbf{s} is a KD dimensional vector which is eventually used for nearest neighbor search using the cosine-distance as metric.

3.3 Normalization

While contrast-normalization is an often used intermediate step in CNN training [1], we employ ZCA whitening to decorrelate the activation features followed by a global L_2 normalization. We will show that the accuracy of the GMM supervector benefits greatly from this normalization step.

Additionally, our GMM supervector is normalized, too. Christlein et al. suggested to normalize the full GMM supervector (consisting of the adapted weight, mean and covariance parameters) using power normalization with a power of 0.5 prior to a L_2 normalization [5]. Effectively this results in applying the Hellinger kernel. In contrast, we employ a kernel derived from the symmetrized Kullback-Leibler divergence [30] to normalize the adapted components:

$$\hat{\boldsymbol{\mu}}_k = \sqrt{w_k \sigma_k^{-\frac{1}{2}}} \tilde{\boldsymbol{\mu}}_k, \quad (4)$$

where σ_k is the vector of the diagonal elements of the covariance matrix Σ of the trained Gaussian mixture k . This implicitly encodes information contained in the variances and weights of the GMM, although only the means were adapted in the main encoding step. The normalized supervector becomes $\hat{\mathbf{s}} = (\hat{\boldsymbol{\mu}}_1^\top, \dots, \hat{\boldsymbol{\mu}}_K^\top)^\top$.

3.4 Implementation Notes

For the computation of the posteriors, we set all but the ten highest posterior probabilities computed from each descriptor to zero. Consequently, we compute the adaptation only for the data having non-zero posteriors. This has the effect of reducing the computational cost with nearly no loss in accuracy. Similar to the work of Christlein et al. [5], we used 100 Gaussian mixtures, but raised the relevance factor τ to 68 which was found to slightly improve the results.

4 Evaluation

4.1 Datasets

We use two different datasets for evaluation: the ICDAR13 benchmark set [20] and the CVL dataset [18]. Both are publicly available and have been used in many recent publications [5,9,15].

ICDAR13 [20] The ICDAR13 benchmark set is separated into a training set consisting of documents from 100 writers and a writer independent test set consisting of documents from 250 writers. Each writer contributed four documents. Two are written in Greek, and two are written in English. This provides for a challenging cross-language writer identification.

CVL [18] The CVL dataset consists of 310 writers. The dataset is split in a training set and a test set without overlap of the writers. The training set contains 27 writers contributing seven documents each. The test set consists of 283 writers who contributed five documents each. One document out of the five (seven) documents is written in German, the others in English. Note that we binarized the documents using Otsu’s method.

4.2 Metrics

To evaluate our experiments we use the mean average precision (mAP) and the hard TOP- k scores. Both are common metrics in information retrieval tasks. Given a query document from one writer, an ordered list of documents is returned, where the first returned document is regarded as being the closest to the query document. The mAP then is the mean of the average precision (aP) over all queries. aP is defined as

$$\text{aP} = \frac{\sum_{k=1}^n P(k) \cdot \text{rel}(k)}{\#\text{relevant documents}}. \quad (5)$$

Table 1: Evaluation of different CNN configurations on the ICDAR13 training set

Filter configuration	C1	P1	C2	P2
A	5×5	2×2	5×5	2×2
B	7×7	2×2	5×5	3×3

(a) Convolutional and pooling layer configurations of the CNN

Filter size	No. hidden nodes			Filter size	No. hidden nodes		
	64	128	256		64	128	256
A	38.2/23.2	49.3/23.7	55.0/24.5	A	0.937	0.926	0.895
B	40.3/21.0	45.6/22.4	53.5/23.0	B	0.948	0.929	0.910

(b) Classification accuracy [%] using the classification layer of the CNN (train/test) (c) Averaged mAP of VLAD encoding

Given the ordered list of documents for a query document, the aP averages over $P(k)$, the precision at rank k , that is given by the number of documents from the same writer in the query up to rank k divided by k . $\text{rel}(k)$ is an indicator function that is one if the document retrieved at rank k is from the same writer and zero otherwise.

The hard TOP- k scores are determined by calculating the percentage of queries, where the k highest ranked documents were from the same writer, e. g., the hard TOP-3 denotes the probability that the three best ranked documents stem from the correct writer.

4.3 Convolutional Neural Network Parameters

With the CNN architecture fixed to two convolutional and one hidden layer there are two main parameters that are essential for the performance of the trained activation features: the filter size, and the number of hidden nodes in the last layer, i. e., the size of the output descriptor. We conducted some preliminary experiments using the ICDAR13 training set to determine the optimal parameters for the chosen network architecture. We evaluated two different setups of the filter and pooling sizes for the convolutional layers. The values for the two configurations **A** and **B** are shown in Table 1a. Comparing the two configurations shows that, **B** uses larger filters and pooling sizes and should therefore be more insensitive to translations of the patches. For both filter sizes we also evaluated the effect of the output feature size by using three different numbers of hidden nodes in the last layer: 64, 128, and 256.

For these preliminary experiments we used VLAD encoding [17] instead of GMM supervectors due to its faster computation time. VLAD is a non-probabilistic version of Fisher vectors which hard-encodes the first order statistics, i. e., $\mathbf{s}_k = \sum_{\mathbf{x}_t \in \tilde{\mathbf{X}}} (\mathbf{x}_t - \boldsymbol{\mu}_k)$, where $\tilde{\mathbf{X}}$ refers to the set of descriptors for which the

Table 2: The influence of different parts of the pipeline on the ICDAR13 test set

Method	mAP	Method	mAP
RootSIFT + $SV_{wmc,ssr+12}$ [5]	0.671	CNN-AF _{pwh} + $SV_{m,kl}$	0.880
RootSIFT + $SV_{m,kl}$	0.680	CNN-AF _{zwh} + $SV_{m,kl}$	0.886
SURF + $SV_{m,kl}$	0.718	CNN-AF _{zwh} + $SV_{wmc,ssr+12}$	0.877
CNN-AF + $SV_{m,kl}$	0.860	CNN-AF _{zwh} + FV	0.866

(a) Comparison of different local descriptors

(b) Influence of different whitening and encoding methods

cluster center μ_k is the closest one. The dictionary can be efficiently computed by using a mini-batch version of k -means [26]. We report the average mAP over the results of 10 VLAD-encoding runs.

Besides the network configurations, Table 1 shows the classification accuracy obtained with the CNN including the classification layer on the test set after 20 epochs of training in part (b) and the averaged mAP of 10 runs of VLAD encoding in part (c). Interestingly, the results for both evaluation approaches are almost complementary. The CNN alone reaches the best results for smaller filters and a large number of hidden nodes, while the VLAD encoding prefers larger filters and a smaller size of the activation features vector (i. e., number of hidden nodes). A possible explanation might be that, for a larger number of hidden nodes the activations of the hidden layer are less descriptive for discerning between writers because the connections between the hidden and the classification layer take over that part. In contrast, for a small number of hidden nodes, the descriptiveness of the activations of the hidden layer seems to be higher, making them more suitable for use as features independent from the classification layer of the CNN. It should also be noted that the classification accuracy of the CNN is already quite impressive considering that the classification is performed using only a single patch of size 32×32 for 100 different writers/classes. Since configuration **B** shows the highest mAP, this configuration of the CNN is used for all of the following experiments.

4.4 Performance Analysis

We now investigate the influence of the individual steps in our pipeline. We replace the CNN activation features by other local descriptors. We also examine the influence of applying ZCA- and PCA-whitening to the CNN activation features. Lastly, we evaluate the replacement of the GMM supervectors with other encoding methods.

Table 2a compares the learned activation features with SURF and RootSIFT. Both have been used successfully for offline writer identification by Jain and Doermann [15] and Christlein et al. [5], respectively. Interestingly, SURF performs

better than RootSIFT. However, our proposed activation features outperform both descriptors by 0.14 and 0.18 mAP, respectively.

Table 2b shows the effect of decorrelating the activation features using PCA and ZCA whitening ($\text{CNN-AF}_{\text{pwh}} + \text{SV}_{\text{m,kl}}$ vs. $\text{CNN-AF}_{\text{zwh}} + \text{SV}_{\text{m,kl}}$) and the comparison with the other encoding methods. $\text{CNN-AF}_{\text{zwh}} + \text{SV}_{\text{wmc,ssr}+l_2}$ is using GMM supervectors as proposed by Christlein et al. [5] and $\text{CNN-AF}_{\text{zwh}} + \text{FV}$ uses Fisher vectors as proposed by Sanchez et al. [24]. The SV encoding by Christlein et al. adapts all components (weights, means, covariances) while the FV encoding uses the means and covariances. Both methods use power normalization (power of 0.5) followed by l_2 normalization instead of the KL-kernel normalization.

The decorrelation of the features brings an improvement of 0.02 mAP, with ZCA giving slightly better results than PCA. The decorrelated score with the proposed method also outperforms the two other encoding methods.

4.5 Comparison with the State of the Art

Table 3a and Table 4 show the results achieved with the complete pipeline on the ICDAR13 and CVL test sets, respectively. We compare with the state of the art ¹ and SURF descriptors encoded with GMM supervectors, cf. Table 2a. Since the CVL training set is too small to compute a comparable GMM, we used the GMM and ZCA transformation matrix estimated on the ICDAR13 training set for evaluating the pipeline on the CVL dataset. On both datasets the proposed pipeline using CNN activation features outperforms the previous methods in terms of mAP. The increase in performance is particularly evident on the complete ICDAR13 test set, where our method achieves an absolute improvement of 0.21 mAP. This is significantly better than the state of the art [5] (permutation test: $p \ll 0.05$). On the CVL dataset we achieve comparable results to the state of the art (permutation test: $p = 0.11$). However note that a) the ICDAR13 dataset is much more challenging due to its bilingual nature, and b) that we have not trained explicitly for the CVL dataset. Thus, our results show that the features learned from the ICDAR training set can generally be used for other datasets, too. We believe that the results could be further improved if the CVL training set would be incorporated into the training of the CNN activation features.

Table 3b shows the results for evaluating the Greek and English subsets of the ICDAR13 test set independently. Again, the proposed method further improves the already high scores of the previous methods.

5 Conclusion

The writer identification method proposed in this paper exploits activation features learned by a deep CNN, which in comparison to traditional local descriptors like SIFT or SURF yield higher mAP scores on the ICDAR13 and CVL datasets. On the ICDAR13 test set, an increase of about 0.21 mAP is achieved with this

¹ The methods [15] and [12] did not provide results on the full ICDAR13 dataset.

Table 3: Hard criterion TOP- k scores and mAP evaluated on ICDAR13 (test set)

	TOP-1 TOP-2 TOP-3 mAP				Greek		English		
					TOP-1	mAP	TOP-1	mAP	
CS [14]	0.951	0.196	0.071	NA	Δ -n H. [12]	0.960	NA	0.934	NA
SV [5]	0.971	0.428	0.238	0.671	Comb. [15]	0.992	0.995	0.974	0.979
SURF	0.967	0.551	0.273	0.718	SURF	0.950	0.965	0.956	0.964
Proposed	0.989	0.832	0.613	0.886	Proposed	0.996	0.998	0.976	0.981

(a) Complete ICDAR13 test set

(b) ICDAR13 language subsets

Table 4: Hard criterion and mAP evaluated on CVL

	TOP-1	TOP-2	TOP-3	TOP-4	mAP
FV [9]	0.978	0.956	0.894	0.758	NA
Comb [15]	0.994	0.983	0.948	0.829	0.969
SV [5]	0.992	0.981	0.958	0.887	0.971
SURF	0.986	0.973	0.948	0.836	0.958
Proposed	0.994	0.988	0.973	0.926	0.978

new set of features. We show in our experiments that the retrieval rate is strongly influenced by the design choices of the CNN architecture. The local activation features are encoded using a modified variant of the GMM supervectors approach. However, we adapt only the means of the Gaussian mixtures in the aggregation step. Subsequently, the supervector is normalized using the KL-kernel. By implicitly adding information contained in the weights and covariances of the mixtures in the normalization step, the performance is increased while at the same time halving the dimensionality of the global descriptor.

For future work, we would like to explore larger and more complex CNN architectures and recent discoveries like the benefit of L_p -pooling [27] instead of max pooling and normalization of activations after convolutional layers of the network. There is also still room for improvement in the encoding step of the local descriptors, where democratic aggregation [16] or higher order VLAD [22] could further improve the writer identification rates.

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