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Letters

$(2D)^2$ PCA: Two-directional two-dimensional PCA for efficient face representation and recognition

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Abstract

Recently, a new technique called two-dimensional principal component analysis (2DPCA) was proposed for face representation and recognition. The main idea behind 2DPCA is that it is based on 2D matrices as opposed to the standard PCA, which is based on 1D vectors. Although 2DPCA obtains higher recognition accuracy than PCA, a vital unresolved problem of 2DPCA is that it needs many more coefficients for image representation than PCA. In this paper, we first indicate that 2DPCA is essentially working in the row direction of images, and then propose an alternative 2DPCA which is working in the column direction of images. By simultaneously considering the row and column directions, we develop the two-directional 2DPCA, i.e. $(2D)^2$ PCA, for efficient face representation and recognition. Experimental results on ORL and a subset of FERET face databases show that $(2D)^2$ PCA achieves the same or even higher recognition accuracy than 2DPCA, while the former needs a much reduced coefficient set for image representation than the latter.

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1. Introduction

Principal component analysis (PCA) [3] is a well-known feature extraction and data representation technique widely used in the areas of pattern recognition, computer vision and signal processing, etc. [2,4]. In the PCA-based face representation and recognition methods [6,9,10], the 2D face image matrices must be previously transformed into 1D image vectors column by column or row by row. However, concatenating 2D matrices into 1D vectors often leads to a high-dimensional vector space, where it is difficult to evaluate the covariance matrix accurately due to its large size and the relatively small number of training samples [7]. Furthermore, computing the eigenvectors of a large size covariance matrix is very time-consuming.

To overcome those problems, a new technique called two-dimensional principal component analysis (2DPCA) [7] was recently proposed, which directly computes eigenvectors of the so-called *image covariance matrix* without matrix-to-vector conversion. Because the size of the image covariance matrix is equal to the width of images, which is quite small compared with the size of a covariance matrix in PCA, 2DPCA evaluates the image covariance matrix more accurately and computes the corresponding eigenvectors more efficiently than PCA. It was reported in [7] that the recognition accuracy on several face databases was higher using 2DPCA than PCA, and the extraction of image features is computationally more efficient using 2DPCA than PCA.

However, the main disadvantage of 2DPCA is that it needs many more coefficients for image representation than PCA [7,8]. For example, suppose the image size is 100×100 , then the number of coefficients of 2DPCA is $100 \times d$, where d is usually set to no less than 5 for satisfying accuracy. Although this problem can be alleviated by using PCA after 2DPCA for further dimensional reduction, it is still unclear how the dimension of 2DPCA could be reduced directly [7]. In this paper, we first indicate that 2DPCA is essentially working in the row direction of images, and then propose an alternative 2DPCA which is working in the column direction of images. By simultaneously considering the row and column directions (see Eq. (8) in Section 4), we develop the 2DPCA, i.e. $(2D)^2$ PCA, for efficient face representation and recognition. Experimental results on ORL and a subset of FERET face databases show that $(2D)^2$ PCA achieves the same or even higher recognition accuracy than 2DPCA, while the number of coefficients needed by the former for image representation is much less than that of the latter. The experimental results also indicate that $(2D)^2$ PCA is more computationally efficient than both PCA and 2DPCA.

The rest of this paper is organized as follows: Section 2 briefly reviews the 2DPCA method; Section 3 presents an alternative 2DPCA method; the proposed $(2D)^2$ PCA method is introduced in Section 4; in Section 5, some experiments on several face databases are given to compare the performances of 2DPCA and $(2D)^2$ PCA; finally, we conclude in Section 6.

2. 2DPCA

Consider an m by n random image matrix \mathbf{A} . Let $\mathbf{X} \in R^{n \times d}$ be a matrix with orthonormal columns, $n \geq d$. Projecting \mathbf{A} onto \mathbf{X} yields an m by d matrix $\mathbf{Y} = \mathbf{AX}$.

In 2DPCA, the total scatter of the projected samples was used to determine a good projection matrix \mathbf{X} . That is, the following criterion is adopted:

$$\begin{aligned} J(\mathbf{X}) &= \text{trace}\{E[(\mathbf{Y} - E\mathbf{Y})(\mathbf{Y} - E\mathbf{Y})^T]\} \\ &= \text{trace}\{E[(\mathbf{A}\mathbf{X} - E(\mathbf{A}\mathbf{X}))(\mathbf{A}\mathbf{X} - E(\mathbf{A}\mathbf{X}))^T]\} \\ &= \text{trace}\{\mathbf{X}^T E[(\mathbf{A} - E\mathbf{A})^T(\mathbf{A} - E\mathbf{A})]\mathbf{X}\}, \end{aligned} \quad (1)$$

where the last term in Eq. (1) results from the fact that $\text{trace}(\mathbf{A}\mathbf{B}) = \text{trace}(\mathbf{B}\mathbf{A})$, for any two matrices [1]. Define the *image covariance matrix* $\mathbf{G} = E[(\mathbf{A} - E\mathbf{A})^T(\mathbf{A} - E\mathbf{A})]$, which is an n by n nonnegative definite matrix. Suppose that there are M training face images, denoted by m by n matrices \mathbf{A}_k ($k = 1, 2, \dots, M$), and denote the average image as

$$\bar{\mathbf{A}} = \frac{1}{M} \sum_k \mathbf{A}_k.$$

Then \mathbf{G} can be evaluated by

$$\mathbf{G} = \frac{1}{M} \sum_{k=1}^M (\mathbf{A}_k - \bar{\mathbf{A}})^T (\mathbf{A}_k - \bar{\mathbf{A}}). \quad (2)$$

It has been proven that the optimal value for the projection matrix \mathbf{X}_{opt} is composed by the orthonormal eigenvectors $\mathbf{X}_1, \dots, \mathbf{X}_d$ of \mathbf{G} corresponding to the d largest eigenvalues, i.e. $\mathbf{X}_{\text{opt}} = [\mathbf{X}_1, \dots, \mathbf{X}_d]$. Because the size of \mathbf{G} is only n by n , computing its eigenvectors is very efficient. Also, like in PCA the value of d can be controlled by setting a threshold as follows:

$$\frac{\sum_{i=1}^d \lambda_i}{\sum_{i=1}^n \lambda_i} \geq \theta, \quad (3)$$

where $\lambda_1, \lambda_2, \dots, \lambda_n$ is the n biggest eigenvalues of \mathbf{G} and θ is a pre-set threshold.

3. Alternative 2DPCA

Let $\mathbf{A}_k = [(\mathbf{A}_k^{(1)})^T (\mathbf{A}_k^{(2)})^T \dots (\mathbf{A}_k^{(m)})^T]^T$ and $\bar{\mathbf{A}} = [(\bar{\mathbf{A}}^{(1)})^T (\bar{\mathbf{A}}^{(2)})^T \dots (\bar{\mathbf{A}}^{(m)})^T]^T$, where $\mathbf{A}_k^{(i)}$ and $\bar{\mathbf{A}}^{(i)}$ denote the i th row vectors of \mathbf{A}_k and $\bar{\mathbf{A}}$, respectively. Then Eq. (2) can be rewritten as

$$\mathbf{G} = \frac{1}{M} \sum_{k=1}^M \sum_{i=1}^m (\mathbf{A}_k^{(i)} - \bar{\mathbf{A}}^{(i)})^T (\mathbf{A}_k^{(i)} - \bar{\mathbf{A}}^{(i)}). \quad (4)$$

Eq. (4) reveals that the image covariance matrix \mathbf{G} can be obtained from the outer product of row vectors of images, assuming the training images have zero mean, i.e. $\bar{\mathbf{A}} = (\mathbf{0})_{m \times n}$. For that reason, we claim that original 2DPCA is working in the row direction of images.

Illuminated by Eq. (4), a natural extension is to use the outer product between column vectors of images to construct \mathbf{G} . Let $\mathbf{A}_k = [(\mathbf{A}_k^{(1)}) (\mathbf{A}_k^{(2)}) \dots (\mathbf{A}_k^{(m)})]$ and $\bar{\mathbf{A}} = [(\bar{\mathbf{A}}^{(1)}) (\bar{\mathbf{A}}^{(2)}) \dots (\bar{\mathbf{A}}^{(m)})]$, where $\mathbf{A}_k^{(j)}$ and $\bar{\mathbf{A}}^{(j)}$ denote the j th column vectors of \mathbf{A}_k

and $\bar{\mathbf{A}}$, respectively. Then an alternative definition for image covariance matrix \mathbf{G} is:

$$\mathbf{G} = \frac{1}{M} \sum_{k=1}^M \sum_{j=1}^n (\mathbf{A}_k^{(j)} - \bar{\mathbf{A}}^{(j)})(\mathbf{A}_k^{(j)} - \bar{\mathbf{A}}^{(j)})^T. \quad (5)$$

Now we will show how Eq. (5) can be derived at a similar way as in 2DPCA. Let $\mathbf{Z} \in R^{m \times q}$ be a matrix with orthonormal columns. Projecting the random matrix \mathbf{A} onto \mathbf{Z} yields a q by n matrix $\mathbf{B} = \mathbf{Z}^T \mathbf{A}$. Similar as in Eq. (1), the following criterion is adopted to find the optimal projection matrix \mathbf{Z} :

$$\begin{aligned} J(\mathbf{Z}) &= \text{trace}\{E[(\mathbf{B} - E\mathbf{B})(\mathbf{B} - E\mathbf{B})^T]\} \\ &= \text{trace}\{E[(\mathbf{Z}^T \mathbf{A} - E(\mathbf{Z}^T \mathbf{A}))(\mathbf{Z}^T \mathbf{A} - E(\mathbf{Z}^T \mathbf{A}))^T]\} \\ &= \text{trace}\{\mathbf{Z}^T E[(\mathbf{A} - E\mathbf{A})(\mathbf{A} - E\mathbf{A})^T] \mathbf{Z}\}, \end{aligned} \quad (6)$$

From Eq. (6), the alternative definition of image covariance matrix \mathbf{G} is:

$$\begin{aligned} \mathbf{G} &= E[(\mathbf{A} - E\mathbf{A})(\mathbf{A} - E\mathbf{A})^T] = \frac{1}{M} \sum_{k=1}^M (\mathbf{A}_k - \bar{\mathbf{A}})(\mathbf{A}_k - \bar{\mathbf{A}})^T \\ &= \frac{1}{M} \sum_{k=1}^M \sum_{j=1}^n (\mathbf{A}_k^{(j)} - \bar{\mathbf{A}}^{(j)})(\mathbf{A}_k^{(j)} - \bar{\mathbf{A}}^{(j)})^T. \end{aligned} \quad (7)$$

Similarly, the optimal projection matrix \mathbf{Z}_{opt} can be obtained by computing the eigenvectors $\mathbf{Z}_1, \dots, \mathbf{Z}_q$ of Eq. (7) corresponding to the q largest eigenvalues, i.e. $\mathbf{Z}_{\text{opt}} = [\mathbf{Z}_1, \dots, \mathbf{Z}_q]$. The value of q can also be controlled by setting a threshold as in Eq. (3). Because the eigenvectors of Eq. (7) only reflect the information between columns of images, we say that the alternative 2DPCA is working in the column direction of images.

4. (2D)²PCA

As discussed in Sections 2 and 3, 2DPCA and alternative 2DPCA only works in the row and column direction of images, respectively. That is, 2DPCA learns an optimal matrix \mathbf{X} from a set of training images reflecting information between rows of images, and then projects an m by n image \mathbf{A} onto \mathbf{X} , yielding an m by d matrix $\mathbf{Y} = \mathbf{A}\mathbf{X}$. Similarly, the alternative 2DPCA learns optimal matrix \mathbf{Z} reflecting information between columns of images, and then projects \mathbf{A} onto \mathbf{Z} , yielding a q by n matrix $\mathbf{B} = \mathbf{Z}^T \mathbf{A}$. In the following, we will present a way to simultaneously use the projection matrices \mathbf{X} and \mathbf{Z} .

Suppose we have obtained the projection matrices \mathbf{X} (in Section 2) and \mathbf{Z} (in Section 3), projecting the m by n image \mathbf{A} onto \mathbf{X} and \mathbf{Z} simultaneously, yielding a q by d matrix \mathbf{C}

$$\mathbf{C} = \mathbf{Z}^T \mathbf{A}\mathbf{X}. \quad (8)$$

The matrix \mathbf{C} is also called the coefficient matrix in image representation, which can be used to reconstruct the original image \mathbf{A} , by

$$\hat{\mathbf{A}} = \mathbf{Z}\mathbf{C}\mathbf{X}^T. \quad (9)$$

When used for face recognition, the matrix \mathbf{C} is also called the feature matrix. After projecting each training image \mathbf{A}_k ($k = 1, 2, \dots, M$) onto \mathbf{X} and \mathbf{Z} , we obtain the training feature matrices \mathbf{C}_k ($k = 1, 2, \dots, M$). Given a test face image \mathbf{A} , first use Eq. (8) to get

the feature matrix \mathbf{C} , then a nearest neighbor classifier is used for classification. Here the distance between \mathbf{C} and \mathbf{C}_k is defined by

$$d(\mathbf{C}, \mathbf{C}_k) = \|\mathbf{C} - \mathbf{C}_k\| = \sqrt{\sum_{i=1}^q \sum_{j=1}^d (C^{(i,j)} - C_k^{(i,j)})^2}. \quad (10)$$

5. Experiments

In this section, we experimentally evaluate our proposed $(2D)^2PCA$ method with PCA, 2DPCA and alternative 2DPCA, on two well-known face databases: ORL and FERET [5]. All of our experiments are carried out on a PC machine with P4 1.7 GHz CPU and 256 MB memory. If without extra explanations, the number of projection vectors in all methods are controlled by the value of θ , which is set to 0.95 in all the experiments.

5.1. Results on ORL database

The ORL database (<http://www.uk.research.att.com/facedatabase.html>) contains images from 40 individuals, each providing 10 different images with size of 112×92 . In this experiment, the first five image samples per class are used for training, and the remaining images for test. Table 1 gives the comparisons of four methods on recognition accuracy, dimensions of feature vector and running times. Table 1 shows that 2DPCA, alternative 2DPCA and $(2D)^2PCA$ achieves the same improvements in accuracy than PCA on this database, while the latter needs much reduced dimension of feature vector for the following classification than the former two. Table 1 also indicates that $(2D)^2PCA$ needs the least running time among the four methods.

To further disclose the relationship between the accuracy and dimension of feature vectors, classification experiments under a series of different dimensions between $(2D)^2PCA$ and PCA, 2DPCA are performed and the results are plotted in Fig. 1(a) and (b), respectively. It can be seen from Fig. 1 that under the same dimensions of feature vectors, $(2D)^2PCA$ obtains better accuracy than both 2DPCA and PCA.

5.2. Results on partial FERET database

This partial FERET face database comprises 400 gray-level frontal view face images from 200 persons, each of which is cropped with the size of 60×60 . There are 71 females and 129 males; each person has two images (**fa** and **fb**) with different

Table 1
Comparisons of four methods on ORL database

Method	Accuracy (%)	Dimension	Time (s)
PCA	88.0	110	26.65
2DPCA	90.5	27×112	7.30
Alternative 2DPCA	90.5	26×92	5.77
$(2D)^2PCA$	90.5	27×26	3.43

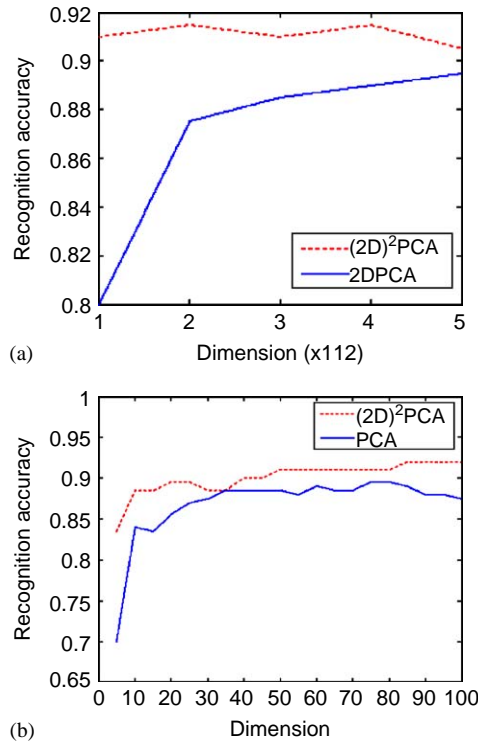


Fig. 1. (a) Comparisons of accuracies between (2D)²PCA and 2DPCA, and (b) between (2D)²PCA and PCA under different dimensions.

facial expressions. The **fa** images are used as gallery for training while the **fb** images as probes for test. Table 2 gives the comparisons of four methods on recognition accuracy, dimensions of feature vector and running times. Also, (2D)²PCA outperforms the other methods in accuracy and speed.

Finally, experiments are carried out to compare abilities of PCA, 2DPCA and (2D)²PCA in representing face images under similar compression ratios. Suppose there are M m by n training face images, the number of projection vectors in PCA, 2DPCA and alternative 2DPCA is p , d and q . Then the compression ratios of PCA, 2DPCA, alternative 2DPCA and (2D)²PCA are computed as $Mmn/(Mp + mnp)$, $Mmn/(Mmd + nd)$, $Mmn/(Mnq + mq)$ and $Mmn/(Mdq + nd + mq)$, respectively. Fig. 2 plots some reconstructed training face images using PCA, 2DPCA and (2D)²PCA on FERET database under similar compression ratios. It can be shown that (2D)²PCA yields higher quality images than the other two methods, when using similar amount of storage.

6. Conclusions

In this paper, an efficient face representation and recognition method called (2D)²PCA is proposed. The main difference between (2D)²PCA and existing 2DPCA

Table 2
Comparisons of four methods on partial FERET database

Method	Accuracy (%)	Dimension	Time (s)
PCA	83.0	73	10.32
2DPCA	84.5	13×60	1.82
Alternative 2DPCA	84.5	14×60	1.80
$(2D)^2PCA$	85.0	13×14	1.15



Fig. 2. Some reconstructed training images on FERET database. First row: original images. Second row: images gotten by PCA. Third row: images gotten by 2DPCA. Bottom row: images gotten by the proposed $(2D)^2PCA$ method.

is that the latter only works in the row direction of face images, while the former works simultaneously in the row and the column directions of face images. The main advantage of $(2D)^2PCA$ over 2DPCA lies in that the number of coefficients needed by the former for face representation and recognition is much smaller than the latter. Experimental results show the effects of the proposed method.

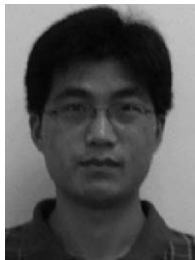
Note that Eqs. (8) and (9) are essentially different from singular value decomposition (SVD). On one hand, the C here is not a diagonal matrix as that used in SVD. On the other hand, in contrast to SVD where the X and Z are only relative to the current matrix A , here the X and Z are computed beforehand and their columns correspond to the eigenvectors of Eqs. (2) and (5), respectively.

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