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Adaptive Hybrid Reduction for Facial Recognition

Djamel Berrabah
University Djillali Liabes of Sidi Bel Abbes

Yacine Gafour
Ibn Khaldoun University of Tiaret

Abstract: The rapid growth of large-scale image datasets has highlighted the importance of dimensionality reduction in improving computational efficiency while preserving critical visual information. This paper investigates both single-method and hybrid approaches to dimensionality reduction for facial recognition, with a particular focus on the Face94 dataset. Four single techniques, PCA, LDA, NMF, and UMAP, are compared against hybrid strategies that combine two or three methods. Experimental results demonstrate that hybrid approaches consistently outperform individual methods, achieving higher accuracy, precision, recall, and F1-score, while maintaining reasonable computational costs. Among them, tri-hybrid combinations such as PCA-LDA-UMAP achieve near-perfect recognition performance, confirming the effectiveness of carefully designed hybridization strategies for robust facial recognition.

Keywords: Facial recognition optimization, Hybridization of reduction algorithm, Feature preservation metrics, Dataset size impact

Introduction

The exponential growth of digital images across diverse applications has positioned facial recognition as a cornerstone technology in computer vision. From security and surveillance to human–computer interaction and multimedia retrieval, the ability to accurately and efficiently recognize faces is critical. However, the high dimensionality of image data poses significant challenges for both storage and computation, making dimensionality reduction an essential step in facial recognition pipelines (Gafour, Berrabah, & Gafour, 2020).

Classical techniques such as Principal Component Analysis (PCA) (Jolliffe & Cadima, 2016), Linear Discriminant Analysis (LDA) (Fisher, 1936), and Non-negative Matrix Factorization (NMF) (Lee & Seung, 1999) have long served as foundational approaches. More recent non-linear methods, notably t-SNE (van der Maaten & Hinton, 2008) and UMAP (McInnes et al., 2018), enable manifold-aware embeddings that better preserve local structure. Each class of methods offers particular strengths—variance preservation (PCA), class separability (LDA), parts-based interpretability (NMF), or manifold preservation (UMAP/t-SNE)—but also specific limitations such as sensitivity to noise, loss of discriminative information, or high computational cost. Consequently, no single technique is universally optimal for all facial recognition scenarios (Liu et al., 2014; Mahmud et al., 2015).

To address these challenges, this paper explores hybrid dimensionality reduction strategies that combine two or three methods sequentially, with the aim of leveraging complementary properties to obtain compact yet discriminative representations. We evaluate these approaches on the Face94 dataset, comparing single methods (PCA, LDA, NMF, UMAP) against dual and tri-method hybridizations. Experimental results demonstrate that certain tri-hybrid combinations (e.g., PCA–LDA–UMAP) attain superior recognition performance while maintaining reasonable computational cost.

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The remainder of this paper is organized as follows. Section 2 reviews related work in dimensionality reduction and facial recognition. Section 3 presents our proposed hybrid approach. Section 4 reports experimental results with comparative analysis. Finally, Section 5 conclude the paper and discusses future research directions.

Related Work

Dimensionality reduction has been widely studied in face recognition to mitigate the high-dimensional nature of image data, reduce computational cost, and enhance generalization. Early foundational work used PCA to reduce dimensionality by finding the directions of greatest variance while projecting face images into lower-dimensional subspaces. PCA often suffers when class separability is important, which motivated the use of LDA, which explicitly optimizes for class separation. Many hybrid models combine PCA and LDA: first applying PCA to reduce noise and dimensionality, then using LDA to sharpen discriminative boundaries (Liu., et al. 2014) or the other way around (Mahmud., et al. 2015). Alternative hybrid approaches have integrated PCA with Gabor wavelets (Cho et al., 2014).

More recent work explores non-linear and multi-stage dimensionality reduction. For example, NMF adds parts-based and non-negativity constraints, which sometimes produce more interpretable features. There are also kernelized extensions of LDA or PCA that map data into higher-dimensional feature spaces to account for non-linear separability (Yang 2011). Additionally, methods like UMAP and t-SNE, or methods preserving manifold structure are used when local geometry matters.

Hybrid approaches beyond simple PCA and LDA are gaining traction: for instance, combining global methods like PCA with local or non-linear embeddings to capture both broad variance and fine structure. Some works integrate neural networks or classifiers such as Support Vector Machines (SVM) or deep architectures to further improve classification after dimensionality reduction (Huang, et al., 2014; Makandar, et al., 2024).

These related methods show that no single technique is universally best: trade-offs exist between accuracy, robustness, computational cost, and memory size. That motivates the exploration of tri-hybrid algorithms and systematic comparison under different parameter settings which motivates our proposed tri-hybrid approach.

Methodology

The rapid expansion of large-scale image datasets has intensified the need for dimensionality reduction, not only to improve computational efficiency in tasks such as classification and retrieval but also to ensure that critical visual information is preserved. Traditional approaches typically apply a single reduction technique, which may fail to balance variance preservation, class separability, and robustness to noise. To address these limitations, we explore hybrid strategies that combine multiple reduction methods. By integrating the strengths of techniques such as PCA, LDA, NMF, and UMAP, our methodology aims to achieve more compact and discriminative representations, enabling both efficient processing and improved recognition accuracy.

Datasets

In this study, we conduct experiments using the Face94 dataset, a widely adopted benchmark in facial recognition research. The dataset contains images of 20 individuals, each represented by 20 samples, with a resolution of 180 × 200 pixels in RGB format. Both male and female subjects are included, and while lighting variations are minimal, the dataset introduces diversity through facial expressions, slight changes in head scale, and appearance differences such as glasses or facial hair.

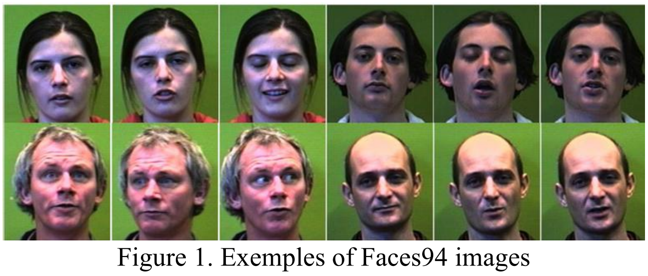

Figure 1. Exemples of Faces94 images

These characteristics make Face94 particularly suitable for evaluating the robustness of dimensionality reduction methods under moderate real-world variations. Figure 1 presents representative examples of facial images drawn from the Face94 dataset.

Approach

We investigated two categories of dimensionality reduction techniques. The first consists of single-method approaches, where one technique is applied independently. Among these, PCA projects data onto directions of maximum variance, LDA maximizes class separability, NMF yields parts-based representations, and UMAP preserves local neighborhood structures through non-linear projection. While effective, each method has limitations such as sensitivity to noise, loss of discriminative information, or high computational cost, indicating that no single technique is universally optimal.

To overcome these shortcomings, we also explore hybrid methods, where two or three techniques are applied sequentially. In dual combinations (e.g., PCA and LDA, PCA and NMF), the first method performs an initial reduction, while the second refines class separability or manifold preservation. In tri-combinations (e.g., PCA, LDA and UMAP), three techniques are integrated to exploit complementary strengths, aiming to produce compact yet highly discriminative feature representations. This comparative framework allows us to assess both the individual contributions of each method and the potential gains achieved through hybridization.

Experimental Pipeline

Our experimental workflow consists of four stages. First, images are preprocessed through grayscale conversion and normalization. Second, dimensionality reduction is applied using either a single method or a hybrid combination. Third, the reduced features are classified using SVM. Finally, performance is evaluated with accuracy, precision, recall, and F1-score, complemented by computational indicators such as execution time, training time, and final model size.

Results and Discussion

Single-method approaches yielded reasonable accuracy, with PCA achieving consistent results. However, hybrid methods consistently outperformed single techniques, confirming the benefits of combining complementary dimensionality reduction strategies. In particular, PCA+LDA improved classification accuracy compared to PCA alone, while tri-combinations achieved even higher performance.

Figure 2. Comparative analysis of performance metrics (left) and computational times (right) for different tri-hybrid combinations

As shown in Figure 2, the left panel compares the performance metrics (Precision, Accuracy, F1, Recall) across different tri-hybrid combinations, where the best-performing models achieve near-perfect values. The right panel reports the execution and training times, highlighting the computational trade-offs among the approaches. While methods involving PCA and LDA yield high accuracy with moderate computational cost, combinations with UMAP often provide superior discriminative power but at the expense of longer execution times.

Overall, the tri-hybrid approaches achieved the best trade-off between accuracy and efficiency, with clear gains in precision, recall, and F1-score compared to single-method baselines. This confirms that carefully designed hybridization strategies are more effective for handling the complexity of high-dimensional facial data.

Table 1. Comparison of tri-hybrid algorithms performances for the Face94 dataset

Combination	Precision	Accuracy	F1	Recall	Execution Time (s)	Training Time (s)
PCA-LDA-NMF	0.64	0.65	0.61	0.65	24.18	0.35
PCA-LDA-UMAP	0.99	0.99	0.99	0.99	54.81	0.12
LDA-NMF-UMAP	0.98	0.97	0.97	0.97	77.57	0.12
NMF-PCA-UMAP	0.78	0.82	0.79	0.82	290.95	0.49
LDA-PCA-UMAP	0.99	0.99	0.99	0.99	81.21	0.12
LDA-PCA-NMF	0.81	0.81	0.81	0.81	61.28	0.22

Table 1 provides a detailed comparison of tri-hybrid combinations on Face94. Among them, PCA-LDA-UMAP and LDA-PCA-UMAP reached near-perfect accuracy (0.99) with balanced precision, recall, and F1-score. In contrast, combinations such as NMF-PCA-UMAP obtained lower accuracy (0.82) and required significantly longer execution times. These results highlight that while hybridization is beneficial overall, the choice of methods strongly impacts both recognition accuracy and computational cost.

Conclusion

This study investigated dimensionality reduction techniques for facial recognition, highlighting the advantages of hybrid strategies. Experiments on Face94 confirmed that hybrid methods surpass single approaches in both accuracy and robustness. Future work will focus on integrating deep learning models into hybrid pipelines, extending evaluation to larger datasets and real-time systems, and analyzing computational trade-offs for deployment on resource-constrained platforms.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest

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Author(s) Information

Djamel Berrabah
Djillali Liabes University of Sidi Bel Abbes
Sidi Bel Abbes, Algeria
Contact e-mail: *berrabdjamel@gmail.com*

Yacine Gafour
Ibn Khaldoun University of Tiaret, Tiaret, Algeria

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