摘 要

自动人脸识别（**AFR**）研究试图赋予计算机根据面孔辨别人物身份的能力。该研究具有重要的科学意义和巨大的应用价值。从学科建设与发展的角度看，**AFR** 作为一个科学问题，是一个典型的图像模式分析、理解与分类计算问题，涉及模式识别，计算机视觉，智能人机交互，图形学，认知科学等多个学科。同时，作为生物特征识别关键技术之一的 **AFR** 技术则在公共安全、信息安全、金融等领域具有潜在的应用前景。

经过三十多年的发展，**AFR** 技术取得了长足的进步，目前最好的 **AFR** 系统在理想情况下已经能够取得可以接受的识别性能。但测试和实践经验表明：非理想条件下的人脸识别技术还远未成熟！要开发出真正鲁棒、实用的 **AFR** 应用系统还需要解决大量的关键问题，尤其需要研究：(1) 作为识别必要前提条件的面部关键特征精确定位问题；(2) 高效的人脸描述特征及其相应的高精度核心识别算法；(3) 如何提高 **AFR** 系统对不可避免的配准错误的鲁棒性问题。另外，对开发鲁棒实用的 **AFR** 系统而言，研究应用系统设计层面的诸多工程技术问题同样至关重要。以设计开发鲁棒、实用的 **AFR** 系统为目标，本文重点探讨了人脸识别中的上述关键问题。本论文的主要贡献总结如下：

1. 全面综述了人脸识别研究的历史和现状

人脸识别研究国内外综述文章最晚也是 2000 年发表的，实际综述内容大多是 1999 年前的文献情况。本文给出的 **AFR** 综述首先探讨了 **AFR** 的一般计算模型，并按照 **AFR** 发展特点，将 **AFR** 研究划分为三个历史阶段，对每个阶段研究的特点以及代表性方法进行了较为详尽的总结，并从面部特征自动定位、人脸表示模型、分类和识别算法三个角度对人脸识别领域的主要方法进行了分类整理。在此基础上，结合近年来主要的人脸识别评测，对人脸识别研究的现状进行了阐述。此外，还总结了现有的主要商业人脸识别系统以及主要的公共人脸图像库的情况。最后讨论了人脸识别领域目前仍然面临的主要开放问题并简单分析了 **AFR** 领域的主要技术趋势。

2. 研究了特征精确配准问题，提出了局部纹理约束的主动表观模型 LTC-AAM

面部特征精确配准是鲁棒实用的人脸识别系统的基本前提。主动形状模型（ASM）和主动表观模型（AAM）是目前解决该问题的主流方法。在对它们的优缺点进行综合分析的基础上，本文对二者进行集成，提出了一种局部纹理约束的主动表观模型 **LTC-AAM**。该模型的要点包括：(1) 继承了 ASM 的局部纹理匹配模型，并针对面部轮廓点采用了边缘增强的局部纹理匹配模型；(2) 在 ASM 形状调整时引入了 AAM 中度量当前纹理与模型纹理匹配度的目标函数，从而将 ASM 形状参数调整规范到了与 AAM 统一的参数优化框架中；(3) 保留了 AAM 利用当前纹理预测表观模型参数变化的启发式参数优化过程。这些特点使得 LTC-AAM 融合了 ASM 局部搜索模型、AAM 纹理约束以及启发式的参数优化过程，从而在较大程度上继承了二者的优势。实验表明，LTC-AAM 能够更精确的定位面部关键特征，为后续的人脸识别打下了良好的配准基础。

3. 研究了 Gabor 特征人脸描述方法，提出了一种 AdaGaDA 人脸识别新方法

良好的人脸表示是鲁棒高效的人脸识别算法的关键因素。Gabor 小波因具有优良的空间局部性和方向选择性，能够提取图像局部区域内多个方向的空间频率和局部结构特征，是一种良好的人脸描述方法。弹性图匹配方法（EGM）和 Gabor 特征 Fisher 判别分类方法（GFC）是应用 Gabor 特征的典型代表。实用系统中 EGM 需要解决关键特征点的定位问题，其速度和精度难以提高；而 GFC 对高维 Gabor 特征直接简单下采样的策略尽管避免了特征定位难题，但却遗漏了大量判别特征。针对这一问题，本文考虑了如何对 Gabor 特征进行有效降维的问题，将 Boosting 策略创新性的应用于

Gabor 特征的优化选择以产生维数较低的 AdaGabor 特征，并最终通过对 AdaGabor 特征的判别分析实现人脸识别——即所谓的 AdaGaDA 人脸识别新方法。在 CAS-PEAL 和 FERET 两个大型人脸图像库上的对比实验表明：AdaGaDA 方法不但可以有效降低 Gabor 特征维数，而且识别精度也比传统方法有了较大提高。

4. 首次提出并系统研究了 AFR 中的“误配准灾难”问题，给出了 AFR 算法误配准鲁棒性能的量化评价方法，提出了一种对误配准进行强化训练的 E-Fisherface 方法，同时还分析了 AdaGaDA 等基于 Gabor 特征的 AFR 方法的误配准鲁棒性

本文首次系统研究了面部特征配准精度对人脸识别算法性能的影响问题，发现 Fisherface 的识别率会随着误配准的增大而急剧下降——本文称这一现象为“误配准灾难”（**COMA**）问题。在分析产生原因的基础上，探讨了 **COMA** 问题的四类解决方案：精确再配准方法、不变特征方法、误配准学习方法和误配准不变距离度量方法。为了量化比较不同识别算法对误配准的鲁棒性，本文提出了一套识别算法误配准鲁棒性能量化评估方法。针对 Fisherface 的“误配准灾难”问题，提出了一种对误配准进行强化训练的 E-Fisherface 方法。还进一步考察了所提出的 AdaGaDA 等基于 Gabor 特征的 **AFR** 方法对误配准的鲁棒性。这些方法在 FERET 和 CAS-PEAL 人脸图像数据库上的对比实验表明：Gabor 特征比单纯的灰度特征具有更强的鲁棒性；对误配准进行强化训练的 E-Fisherface 方法可以大大提高识别系统的鲁棒性。

5. 初步探讨了 AFR 应用系统设计中的共性关键问题，实现了三种应用原型系统

核心识别算法的性能当然是实用人脸识别应用系统最终识别性能的决定性因素，但系统设计是否合适同样在很大程度上影响着应用系统的成败，尤其在人脸识别技术尚未完全成熟的今天，良好的系统设计可能起到事半功倍的效果，而拙劣的系统设计可能会葬送最好的核心识别算法的前途。鉴于此，本文初步探讨了人脸识别应用系统设计中需要考虑的一些共性关键问题，如现场环境设计、摄像设备选择与安装、注册原型图像的挑选、核心算法选择标准、学习集选择、模型在线更新等。最后，基于本文提出的核心技术和关键问题解决方案，给出了人脸照片比对系统、模拟的 XP 用户自动登录系统和机场登机旅客身份验证系统三个典型 **AFR** 应用原型系统的设计方案。

本论文的上述研究内容不但在人脸识别理论层面具有一定的参考价值，更关键的是本文的研究结果对于设计开发鲁棒、实用的 **AFR** 系统具有一定的借鉴意义，所提出的若干关键技术已经获得了实际应用。

关键词：自动人脸识别（AFR），生物特征识别，面部特征配准，主动形状模型（ASM），主动表观模型（AAM），Gabor 小波，主成分分析，Eigenface，线性判别分析，Fisherface，AdaBoost，重采样技术，AdaGabor 特征，AdaGaDA 方法，误配准灾难（COMA），误配准鲁棒性

Study on Some Key Issuses in Face Recognition

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Automatic Face Recognition (AFR) aims at endowing computers with the ability to identify different human beings according to his/her face image. Such a research has both significant theoretic values and wide potential applications. As a scientific issue, AFR is a typical pattern analysis, understanding and classification problem, closely related to many disciplines such as Pattern Recognition, Computer Vision, Intelligent Human-Computer Interaction, Computer Graphics, and Cognitive Psychology etc. Its research achievements would greatly contribute to the development of these disciplines. While as one of the key technologies in Biometrics, AFR techniques are believed having a great deal of potential applications in public security, law enforcement, information security, and financial security.

After more than 30 years' development, AFR has made great progress especially in the past ten years. The state-of-the-art AFR system can perform identification successfully under well-controlled environment. However, evaluation results and practical experience have shown that AFR technologies are currently far from mature. A great number of challenges are to be solved before one can implement a robust practical AFR application. The following key issues are especially pivotal: (1) the accurate facial feature location problem, which is the prerequisite for sequent feature exaction and classification; (2) efficient face representation and corresponding classifier with high accuracy; (3) how to improve the robustness of AFR to inevitable mis-alignment of the facial feature. In addition, elaborate system design is also as important for developing robust and practical AFR systems. In this thesis, the above-mentioned key issues are studied, aiming at robust and practical AFR systems. And the main contribution of this thesis includes:

1. Provided a thorough survey of the AFR history and the state-of-the-art

The latest AFR survey was published in the year 2000, which in fact surveyed the AFR researches before 1999. This thesis has provided a more recent overview of the AFR research and development. The survey starts from the discussion of the general computational model of AFR methods. Then, the AFR researches are partitioned to three historical stages according to the characteristics of technical mainstreams. For each stage, its technical characteristics are summarized and typical milestone methods are mentioned. After that, AFR methods are further categorized according to facial feature extraction, face representation, and classification separately. We also survey the main public face databases and performance evaluations protocols, based on which the state-of-the-arts of AFR are summarized. Main commercial systems are introduced as well with their technical sources. Finally, the challenges and technical trends in AFR fields are discussed.

2. Studied facial feature alignment problem, and proposed a Local Texture Constraint Active Appearance Model.

Accurate facial feature alignment is the prerequisite of an AFR system. Active Shape Model

(ASM) and Active Appearance Model (AAM) are the main methods for this problem. On the basis of analyzing their merits and demerits, LTC-AAM is proposed by combining the ASM and AAM. The main points of LTC-AAM include: (1) Inherit the local texture matching model in ASM and enhanced the local texture model for facial contour landmarks by exploiting explicitly the edge constraints; (2) As in AAM, the energy function measuring the matching degree between the model texture and present texture are acted on active shape searching, therefore the shape parameter adjusting in ASM is unified into the same framework of variable optimization in AAM; (3) Linear prediction of the appearance parameter variance using the present texture as in AAM is retained for the heuristic search in the variable optimization procedure. These points have made LTC-AAM integrate the strengths of ASM's local searching model, AAM's global texture constraints and AAM's heuristic parameter optimization. Therefore, our experiments have illustrated the better performance of LTC-AAM on face alignment.

3. **Investigated the Gabor wavelet face representation method, and proposed a AdaGaDA-based AFR approach.**

Efficient face representation is the key for a good AFR method. For its eminent characteristics in spatial local feature exaction and orientation selection, Gabor-based face representation has attracted much attention. Elastic Graph Matching (EGM) and Gabor feature Fisher Classification (GFC) are typical approaches using Gabor features. However, EGM needs to accurately localize tens of facial landmarks, which would slow down the recognition speed and accuracy. While the GFC simply down-samples the high-dimensional Gabor features evenly, many discriminating features may be lost, though this has avoided the challenging accurate feature alignment. Against this problem, this thesis innovatively proposes an AdaBoost-based Gabor feature dimension reduction method. Boosting techniques are exploited to select low-dimensional AdaGabor features with much discriminating power. Those selected AdaGabor features are classified by Fisher linear discriminant analysis to achieve final identification, which is named by AdaGaDA face recognition approach. Experiments on FERET and CAS-PEAL face database have illustrated that AdaGaDA has efficiently reduced the dimension of the Gabor representations, and the recognition performance has also greatly improved compared with traditional methods.

4. **Initially proposed and investigated the "Curse of mis-alignment" problem; Presented a set of quantitative measurements evaluating AFR method's robustness to mis-alignment; Proposed E-Fisherface to enhance the robustness of Fisherface to mis-alignment by perturbation learning in the model training stage; The robustness of AdaGaDA and GFC are also analyzed theoretically and evaluated experimentally.**

This paper initially studies how the facial feature alignment accuracy influences the face recognition performance. We discover that the performance of Fisherface degrades abruptly with the increase of mis-alignment degree. This paper defines this phenomenon as "Curse of Mis-alignment" (COMA) problem. Based on the analysis of its cause, four categories of solutions to COMA are discussed, that is, alignment-retuning method, mis-alignment robust feature-based method, mis-alignment learning method, and mis-alignment invariant distance measurement method. To quantitatively measure and compare the robustness of different AFR approaches, a set of quantitative measurements evaluating AFR method's robustness to mis-alignment are proposed. Afterwards, aiming at the COMA problem of Fisherface, an E-Fisherface method is proposed to

enhance the robustness of Fisherface to mis-alignment by perturbation learning in the model training stage. The robustness of AdaGaDA and GFC to mis-alignment is also analyzed theoretically and evaluated experimentally. The experimental evaluations on FERET and CAS-PEAL face database have shown that Gabor feature are more robust to mis-alignment compared with the pure image gray-level intensity feature, and the proposed E-Fisherface can greatly improve the robustness of the Fisherface methods.

5. Primarily studied on some common key issues in AFR system design, and implemented three prototype AFR systems.

The overall performance of AFR systems certainly depends mainly on the kernel AFR algorithm, however, system design strategies would further impact the overall performance of AFR systems. This point is even more reasonable nowadays, given that most present AFR technologies are far from mature. Favorable system design would greatly facilitate the recognition procedure, while a bad one may degrade terriblely a best AFR technique. Therefore, some common key issues in AFR system design are briefly discussed, such as the workplace environment design and rebuild, imaging equipment selection and installation, selection of registration prototype images, selection of kernel recognition algorithm, learning set construction, model updating etc. Finally, based on the techniques proposed in this thesis, three prototype AFR systems, facial photo matching system, simulated XP face logon system, and airport passenger verification system, are implemented for demonstration purpose.

The research achievements of this thesis would not only contribute to the AFR computation theory, but also facilitate the development of robust and practical AFR applications. Some of these technologies have been successfully applied to practice.

Keywords：Automatic face recognition (AFR), Biometrics, face alignment, Active Shape Models, Active Appearance Models, Gabor wavelet, Principal Component Analysis (PCA), Eigenface, Linear Discriminant Analysis, Fisherface, AdaBoost, Re-sampling technologies, AdaGabor features, AdaGaDA face recognition method, Curse of mis-alignment, Robustness to mis-alignment