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生物特征识别学科发展报告(2021—2025)

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摘要: 生物特征识别技术已深度融入公共安全、金融支付、智能终端、政务服务等关键领域, 凭借其唯一性、安全性与便捷性, 成为生产生活中不可或缺的核心身份识别手段。从人脸识别的广泛普及到虹膜识别的高安全应用, 从指纹识别的成熟落地到掌纹识别的非接触式创新, 各类生物特征技术在算法演进与场景适配中不断突破。近年来, 深度学习的爆发式发展推动技术从传统手工特征提取迈向深度表征学习, 传感器技术的发展进一步拓展了技术边界, 使得生物特征识别在复杂环境适应性、识别精度与效率上持续进步。然而, 技术泛化部署的背后, 安全威胁与应用挑战也日益凸显。深度伪造、对抗性攻击等新型风险持续冲击技术安全底线, 隐私保护与数据合规成为不可忽视的议题。同时, 跨场景适配、低质量样本识别、资源受限设备部署等现实需求, 推动技术向更鲁棒、高效、通用的方向演进。此外, 生物特征技术正逐步跨界融合, 在人机交互、医疗健康等领域开辟新方向, 实现从身份感知到更全面感知的功能延伸。本报告系统梳理人脸、虹膜、指掌纹、指掌静脉、人体、步态等核心模态的研究现状, 深入剖析技术安全攻防体系, 全面展现其跨界应用成果, 为把握学科发展脉络、探索未来创新方向提供综合参考。

关键词: 生物特征识别; 人脸识别; 虹膜识别; 指掌纹识别; 指掌静脉识别; 行人重识别; 步态识别; 伪造检测

Biometrics disciplinary development report (2021-2025)

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Abstract: Biometric recognition has become a fundamental enabling technology for modern digital society, serving as a core infrastructure for identity authentication, access control, and human-centered intelligence. By exploiting intrinsic physiological and behavioral characteristics, biometrics offers inherent advantages over traditional knowledge- or token-based authentication mechanisms, including higher security, improved usability, and stronger resistance to impersonation. Over the past decade, and especially since 2021, the rapid advancement of deep learning, sensing technologies, and large-scale data resources has profoundly reshaped the landscape of biometric research and applications. Biometric systems have evolved from task-specific, handcrafted pipelines into data-driven, end-to-end intelligent systems capable of operating in complex, unconstrained, and large-scale real-world environments. This report provides a comprehensive review of the development of biometric recognition technologies from 2021 to 2025, covering both methodological advances and emerging application paradigms. We focus on major biometric modalities, including face, iris, fingerprint, palmprint, finger and palm vein, body, gait, and person re-identification, while also highlighting the increasingly critical role of security, privacy protection, and trustworthiness in biometric systems. Face recognition remains the most widely deployed biometric modality due to its non-contact nature, low acquisition cost, and high social acceptance. Recent progress has been driven by innovations in network architectures, large-scale training data, and discriminative loss functions. Convolutional neural networks and vision transformers have significantly improved representation capacity, while margin-based and quality-aware losses have enhanced intra-class compactness and inter-class separability. At the same time, face detection and alignment have advanced toward robust performance under extreme conditions such as low resolution, severe illumination variation, occlusion, and large pose changes. Beyond recognition, face generation and synthesis have emerged as both an enabling technology and a security challenge. Generative adversarial networks and diffusion models now support high-fidelity, controllable, and even 3D-aware face generation, facilitating data augmentation, virtual humans, and animation, while simultaneously raising new threats in the form of deepfakes and identity spoofing. Iris recognition continues to be regarded as one of the most secure biometric modalities due to the high uniqueness and stability of iris texture. In recent years, research has shifted from controlled laboratory settings toward less constrained and mobile scenarios. Advances in iris acquisition include visible-light imaging, mobile-device-based capture, and near-eye sensing in VR/AR environments. Deep learning-based iris segmentation and localization methods have greatly improved robustness against noise, occlusion, and cross-domain variations. In parallel, iris feature representation has evolved from handcrafted binary codes toward deep embeddings and hybrid models that preserve compatibility with traditional matching schemes. Synthetic iris data generation has gained attention as a means to address data scarcity and privacy constraints, although its impact on large-scale recognition performance and potential security implications remain open research questions. Fingerprint recognition, as one of the most mature biometric technologies, has undergone a significant transformation with the adoption of deep learning. Modern fingerprint systems address challenges such as low-quality latent prints, partial fingerprints, distortion, and cross-sensor variability through deep enhancement, minutiae extraction, dense descriptors, and multi-stage matching frameworks. The emergence of new fingerprint modalities, including contactless fingerprints, 3D fingerprints, and optical coherence tomography (OCT)-based internal fingerprints, has expanded the representational space of fingerprint biometrics and enabled improved robustness against distortion and spoofing. At the same time, large-scale real and synthetic fingerprint datasets have facilitated systematic evaluation and training of deep models. Palmprint and palm-vein recognition have experienced rapid growth in both research and large-scale deployment. Advances in deep learning have addressed long-standing challenges in region-of-interest extraction, alignment, and feature robustness, enabling commercial applications such as contactless palm payment systems. Multimodal fusion of palmprint and vein patterns has further enhanced recognition accuracy and security. In addition, progress in palm image synthesis and 3D palm modeling has opened new directions for data augmentation and unconstrained recognition. Body-based biometrics, including person re-identification and gait recognition, play an increasingly important role in surveillance and public safety scenarios where close-range or cooperative acquisition is not feasible. Recent work has focused on cross-view, cross-domain, and long-term recognition under clothing changes, occlusion, and low-resolution conditions. Deep spatiotemporal modeling, attention mechanisms, and sequence-level repre-

sentations have significantly improved robustness, while also raising concerns about privacy, fairness, and ethical deployment. Alongside performance improvements, security and privacy have become central themes in biometric research. Biometric systems are increasingly exposed to sophisticated attacks, including presentation attacks, adversarial examples, template inversion, and deepfake-based impersonation. Consequently, substantial efforts have been devoted to spoof detection, adversarial defense, secure template protection, and cancellable biometrics. Privacy-preserving techniques such as template transformation, encryption, and federated or decentralized learning are gaining importance as regulatory requirements and public awareness intensify. Ensuring that biometric systems are not only accurate but also trustworthy, explainable, and compliant with data protection regulations is now a core research objective. Beyond identity authentication, biometrics is expanding toward broader human-centered applications, including human-computer interaction, healthcare monitoring, behavioral analysis, and immersive virtual environments. This shift reflects a transition from “who you are” to “how you are,” where biometric signals contribute to comprehensive perception and intelligent interaction rather than mere identification. In summary, the period from 2021 to 2025 has witnessed rapid and multifaceted progress in biometric recognition. Advances in deep learning, sensing, and data generation have substantially improved accuracy, robustness, and scalability across modalities, while new challenges in security, privacy, and societal impact have emerged. By systematically reviewing recent developments across core biometric technologies and security frameworks, this report aims to provide a holistic perspective on the current state of the field and to outline promising directions for future research and deployment. We hope this work will serve as a valuable reference for researchers, engineers, and policymakers seeking to understand and shape the next generation of biometric systems.

Key words: Biometrics; Face recognition; Iris recognition; Fingerprint and palmprint recognition; Finger and palm vein recognition; Person re-identification; Gait recognition; Spoof detection

0 引言

随着人类社会向数字化、智能化的发展,身份认证作为信息安全与服务便捷化的核心环节,正经历着从传统密码、卡片等外部凭证向生物特征这一与生俱来的身份标识的革命性转变。生物特征识别技术凭借人体生理特征或行为特征的唯一性、稳定性与不易伪造性,突破了传统认证方式易丢失、易泄露、易伪造等局限。从日常出行的人脸识别门禁、手机解锁的指纹验证,到金融交易的虹膜支付、公共安全的步态追踪,生物特征识别技术正以多元化的形态深度融入社会生产生活的各个领域,重塑着身份认证的效率与安全边界(Jia等,2024)。

生物特征识别技术涵盖了人脸识别、虹膜识别、指纹识别、掌纹识别、指掌静脉识别、人体识别、步态识别等多个核心模态,每种模态均依托独特的生理机制展现出差异化的技术优势与应用场景。人脸识别以其非接触性、便捷性和高准确率成为应用最广泛的模态,在公共安全、移动终端等领域发挥着重要作用;虹膜识别凭借虹膜纹理的极高唯一性与稳定性,成为高安全需求场景的首选;指纹识别则凭借技

术成熟度与硬件适配性,在刑侦、移动终端与安防门禁市场应用非常广泛;指掌静脉识别融合了活体检测的天然优势,在隐私保护要求较高的场景中快速崛起;人体和步态识别则以远距离、非配合式识别的特性,成为视频监控与公共安全领域的重要补充。这些技术模态相互协同,构建起覆盖不同安全等级、不同应用场景的多元化生物识别技术体系。

随着深度学习技术的迅猛发展,整个生物特征识别领域实现了从传统手工特征提取到深度表征学习的跨越式升级,在识别精度、鲁棒性与场景泛化性上取得了突破性进展。然而,技术的广泛部署也带来了新的挑战:一方面,生成式人工智能的崛起使得深度伪造、对抗性攻击等新型安全威胁层出不穷,物理呈现攻击与数字注入攻击的交织让系统安全防护面临严峻考验;另一方面,数据隐私保护法规的完善与公众隐私意识的提升,对生物特征模板的安全存储、合规使用提出了更高要求。同时,在复杂环境下的低质量样本识别、跨设备跨场景的泛化能力、资源受限设备的轻量化部署等问题,仍是制约技术广泛落地的关键瓶颈。

在此背景下,本报告系统梳理了人脸识别、虹膜识别、指纹识别等七大核心模态的研究现状,深入剖

析了各技术环节的前沿进展与现存问题;聚焦生物特征识别的安全挑战,全面阐述了呈现攻击检测、深度伪造取证、隐私模板保护等防御技术的发展脉络;拓展了生物特征识别技术的应用边界,探讨了在人机交互、医疗健康等领域的创新应用。旨在通过全面、系统的研究综述,展现生物特征识别技术的发展全貌,为相关领域的研究人员、技术开发者与政策制定者提供参考,推动技术持续演进。孙哲南等人(2021)的《生物特征识别学科发展报告》对2021年之前的生物特征识别研究进行了总结,本报告侧重于2021年以来的进展。表1列出了本文覆盖的主要内容。

表1 生物特征识别学科发展报告主要内容

Table 1 Content of biometrics disciplinary development report

生物特征	身份识别	身份识别安全	新型应用
人脸	检测、对齐识别、生成	呈现攻击深度伪造统一检测	表情识别 生理信号
虹膜	图像采集、分割、特征表达、生成	活体检测	
指纹	特征提取匹配、生成新采集模态	攻击检测	人机交互
掌纹	采集、对齐、识别质量评估生成、多模态	呈现攻击对抗攻击隐私保护	
静脉	图像库获取特征表达场景适应	呈现攻击对抗攻击模版保护	健康监测
行人	弱监督多模态视频序列鲁棒性	对抗攻击后门攻击隐私保护	
步态	特征表达大模型非监督	隐私保护	

1 生物特征识别

在诸多生物特征识别技术中,人脸识别、虹膜识

别和指纹识别是最为重要且应用最为广泛的。最近几年,掌纹识别、掌静脉识别、指静脉识别、行人重识别、步态识别等新兴技术发展迅速,而且逐步开始有大规模的应用。本章对上述几种最具代表性生物特征识别技术的近期研究现状进行总结,概要论述这些技术的主要研究进展。

1.1 人脸识别研究现状

人脸识别因其准确性高、采集便捷、成本低廉以及非接触、低侵扰等优势,已成为当前应用最广泛的生物识别技术之一,在安防、金融及公共管理等领域得到广泛应用。



图1 YOLO-FaceV2 小人脸检测示例(Yu等,2024)

Fig. 1 YOLO-FaceV2 small face detection example

1.1.1 人脸检测

人脸检测是人脸识别系统的基础环节,其任务是在图像或视频中准确定位人脸区域。该问题长期受到尺度变化、复杂光照和遮挡等因素的影响。近年来,深度学习显著推动了人脸检测技术的发展。

基于目标检测框架的研究成为主流方向。YOLO-Face(Chen等,2021)通过重新设计锚框尺寸和比例,并引入新的回归损失函数,有效提升了小尺度人脸的检测性能。YOLO5Face(Qi等,2022)将人脸检测统一建模为目标检测问题,并结合关键点回归,实现了精度与实时性的平衡。Yu等人(2024)通过改进网络模块和损失函数,加强了对小人脸的特征建模能力。ASFD(Li等,2021)利用可微架构搜索实现特征融合模块的自动设计,在性能与效率之间取得良好折中。HLA(Wang等,2021)与Yu等人(2021)的研究则分别针对低光照和弱光环境,通过特定增强策略提升检测鲁棒性。此外,ATDetect(Lau等,2023)和VED-Net(Xu等,2025)进一步扩展了人脸检测在远距离、多任务和低光照场景下的应

用能力。

总体而言,现有方法在人脸检测精度和效率方面取得了显著进展,但在极端环境和复杂场景下仍存在改进空间。



图2 EfficientFAN人脸对齐结果图(Gao等,2023)

Fig. 2 The face alignment result image of EfficientFAN

1.1.2 人脸对齐

人脸对齐主要关注人脸关键点的精确定位,是后续识别和分析任务的重要基础。早期方法主要依赖统计模型或传统机器学习算法,在复杂场景下泛化能力有限。当前主流方法基于深度神经网络,可分为坐标回归方法(Feng等,2018)和热力图回归方法(Lan等,2021)两类。

近年来,多项研究从网络结构和损失函数设计角度提升关键点检测性能。Wan等人(2023)通过转换参考热力图信息提高检测精度;Li等人(2022)在级联Transformer中引入可变形注意力机制以增强局部特征建模能力;Zhou等人(2023)针对语义歧义问题提出STAR损失以缓解预测分布各向异性。POPoS(Xiang等,2025)和Zeng等人(2023)分别通过距离图优化和生成式数据构建提升了定位精度与鲁棒性。与此同时,SAAT(Zhu等,2021)、EfficientFAN(Gao等,2023)和PIPNet(Jin等,2021)在鲁棒性、轻量化和实时性方面取得了良好效果。

尽管人脸对齐技术不断进步,但在资源受限环境及大姿态、强遮挡条件下同时兼顾精度与效率仍是研究难点。

1.1.3 人脸识别

人脸识别技术已全面进入深度学习阶段。DeepFace(Taigman等,2014)和FaceNet(Schroff等,2015)验证了深度模型在人脸识别中的有效性。当

前性能提升主要依赖于网络结构、大规模数据集和判别性损失函数。卷积神经网络(Convolutional Neural Network, CNN)(Zhao等,2025;Kim等,2022;Zhou等,2023)与视觉Transformer(Dan等,2023;Kim等,2024;An等,2021)是主流特征提取框架。大规模数据集如Glint360K(An等,2021)和WebFace42M(Zhu等,2021)显著增强了模型泛化能力。

图4 人脸生成的代表性方法

Fig. 4 Representative methods for face generation

在损失函数方面,ArcFace(Deng等,2019)、AdaFace(Kim等,2022)、UniFace(Zhou等,2023)和GFace(Zhao等,2025)通过引入角度间隔、自适应权重和全局约束等机制,进一步提升了特征判别性。随着隐私问题日益突出,基于合成数据的人脸识别方法逐渐兴起。SynFace(Qiu等,2021)、Arc2Face(Papantoniou等,2024)、UIFace(Lin等,2025)和Vec2Face(Wu等,2025)表明,在合理建模身份一致性和多样性的前提下,合成数据可有效支持人脸识别模型训练。

尽管如此,在低质量图像和超大规模身份场景下,人脸识别系统仍面临精度稳定性和误识累积等现实挑战。

1.1.4 人脸生成

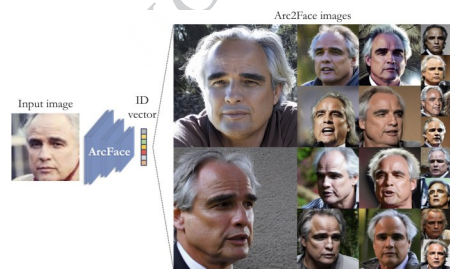


图3 ArcFace合成人脸数据(Papantoniou等,2024)

Fig. 3 ArcFace synthesizes facial data

人脸生成技术近年来在视觉质量、可控性和三维一致性方面持续演进。二维生成方法以生成对抗网络(Generative Adversarial Networks, GAN)和扩散模型为代表,DCGAN(Radford等,2015)、Progressive GAN(Karras等,2017)和StyleGAN系列(Karras等,2019;2021)显著提升了生成质量与可控性。扩散模型DDPM(Ho等,2020)在训练稳定性和多样性方面展现出优势。

为克服二维生成在视角一致性上的不足,三维
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感知生成方法逐步兴起。EG3D(Chan等,2022)、Next3D(Sun等,2023)和EG²3D(Li等,2025)通过引入三维结构建模,实现多视角一致的人脸生成。在此基础上,条件可控生成方法如LivePortrait(Guo等,2024)、IC-Light(Zhang等,2024)和Animate Anyone(Hu等,2024)进一步增强了姿态、表情和光照控制能力。前馈式方法如FaceLift(Lyu等,2024)和LAM(He等,2025)则在保证生成质量的同时显著提升了效率。

总体来看,人脸生成技术正从高质量二维生成向融合三维感知与高效前馈的可控生成方向演进,为虚拟人和沉浸式应用提供了重要支撑。

1.2 虹膜识别研究现状

虹膜识别是一种基于人眼虹膜独特纹理特征进行身份识别的生物特征识别技术,具有准确性高、稳定性强和支持活体检测等优势,广泛应用于金融、安防和司法等高安全场景,并逐步拓展至煤矿、移动支付和VR/AR等领域。典型虹膜识别流程包括图像采集、预处理(活体检测、分割、归一化与增强)以及特征提取与匹配。

1.2.1 虹膜图像采集

虹膜图像采集是虹膜识别系统的入口,其质量直接决定系统性能上限。受制于微小目标成像、高分辨率需求以及亚洲人群高色素虹膜的光学特性,传统虹膜采集通常依赖近红外成像并局限于受控环境。当前制约虹膜识别大规模应用的关键瓶颈在于采集范围受限和用户配合度要求高。

随着移动终端、光学成像和生成技术的发展,虹膜采集正从“专用设备、受控场景”向“泛在终端、开放场景”转变,呈现出以下趋势:一是面向移动端的可见光虹膜采集,如CUVIRIS数据集(Venkataswamy等,2024)推动了跨光谱识别研究;二是VR/AR环境下的近眼采集,如ImmerIris(Mi等,2025)和VRBiom(Kotwal等,2025);三是面向算法公平性的跨种族采样,如CASIA-Iris-Africa(Muhammad等,2024);四是全生命周期与特殊对象采集,如ND-NBSI-2025(Bhuiyan等,2025)和UND-SFI-2024(Bhuiyan等,2024);五是隐私保护驱动下的合成数据生成与攻击研究,如Wang等(2022)和LivDet-Iris 2023(Tinsley等,2023)。

1.2.2 虹膜分割

虹膜分割是虹膜识别中最具挑战性的预处理任

务,其目标包括虹膜内外边界定位及无噪声纹理区域分割(Nguyen等,2024),结果直接用于后续的虹膜归一化,如图5所示。传统方法在受控场景下表现良好,但在非受控环境中易受遮挡、镜面反射和模糊等因素影响。近年来,基于深度学习的方法在分割精度和鲁棒性方面取得显著进展。

早期研究多聚焦于逐像素分割任务,通过引入双注意力网络(Chen等,2021)、Transformer编解码结构(顾等,2022)和图神经网络(Wei等,2024)提升边界建模能力。针对不确定性和跨域问题,Wei等(2025)和Lin等(2026)分别从不确定性建模和域自适应角度提升模型泛化能力。

为同时完成分割与定位任务,多任务框架逐渐成为主流。Wang等(2020)首次联合建模虹膜区域与边界语义,引发后续研究。IrisGazeSeg(Lu等,2022)、Iris R-CNN(Feng等,2022)、IrisST-Net(Liu等,2023)及SFNet(Wang等,2025)在精度、效率和轻量化方面持续改进。与此同时,近红外虹膜挑战赛NIR-ISL 2021(Wang等,2021)和免分割直接虹膜定位方法(Toizumi等,2023)进一步推动了非受控场景下虹膜分割与定位的发展。

针对分割结果可靠性问题,研究者提出了质量评估与不确定性感知方法,如基于聚类的质量检测(Ejiogu等,2023)和贝叶斯不确定性建模的EyeSeg(Peng等,2025)。

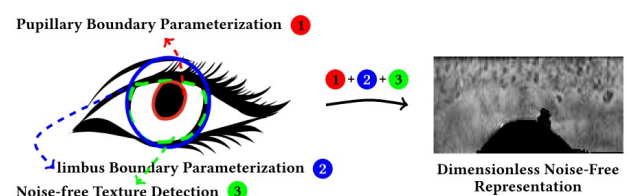


图5 虹膜分割示意图(Nguyen等,2024)

Fig. 5 An illustration of iris segmentation

1.2.3 虹膜特征表达

虹膜特征表达旨在从复杂纹理中提取判别性身份信息。当前深度学习方法整体优于传统手工特征,主要分为两类:一类学习虹膜的空间二值特征;另一类提取嵌入空间中的实值特征向量。

在第一类方法中,UniNet(Zhao和Kumar,2017)、改进残差网络(Wang和Kumar,2019)、ComplexIrisNet(Nguyen等,2023)以及DeepGabor(Proença,2022)通过模拟IrisCode编码过程提升识

别性能; IrisFormer(Sun 等, 2025)进一步利用Transformer提升对旋转和噪声的鲁棒性。第二类方法中, Wei 等(2022; 2022b; 2023)从跨设备识别、不确定性嵌入和上下文建模等角度系统提升了非受控虹膜识别性能。

鉴于虹膜模板不可更换的特性, 可撤销虹膜识别研究逐渐受到关注(Lee 等, 2022; 赵等, 2025; Zhou 等, 2025), 为隐私保护提供了重要支撑。

1.2.4 虹膜合成

受制于数据采集难度和隐私限制, 虹膜识别常面临训练数据规模不足的问题。为此, 研究者引入GAN和扩散模型生成可控虹膜图像。BiOcularGAN(Tomašević 等, 2022)支持多光谱虹膜生成; Wang 等(2022)通过身份与条件解耦生成大规模合成数据, 显著提升识别性能; DeformIrisNet(Khan 等, 2023)通过身份保持的纹理变形增强识别鲁棒性。此外, 针对噪声虹膜修复与补充的研究(张等, 2022; 王等, 2023; Huang 等, 2023; Li 等, 2024)进一步提升了系统实用性。

总体而言, 虹膜合成需同时满足严格拓扑结构与随机纹理分布约束, 其规模化应用及性能增长规律仍有待深入研究。

1.2.5 虹膜识别发展趋势

当前受控条件下的虹膜识别技术已较为成熟, 深度学习推动了非受控场景下在分割、活体检测、特征表达和合成等方面的进展。随着VR/AR等新兴应用的发展(Mi 等, 2025), 未来虹膜识别系统将向“低配合、高通量、高安全”方向演进。这一目标需结合硬件成像提升与算法鲁棒性增强, 并兼顾隐私与安全需求。相关探索包括眼周补充模态(Zhou 等, 2025)、序列虹膜识别(Li 等, 2025)以及通用基础模型在虹膜任务中的适配(Farmanifard 等, 2025; Jiang 等, 2025; Tapia 等, 2025; Sony 等, 2025)。

1.3 指纹识别研究现状

指纹是应用最为广泛的生物特征之一, 在公安安防、移动终端和出入境管理等领域发挥着重要作用。随着传感器技术进步、深度学习方法普及及应用场景复杂化, 指纹识别技术逐步由传统特征工程方法向深度网络建模演进, 涵盖指纹特征提取、识别、新模式采集及数据构建等多个方面。

1.3.1 指纹特征提取

指纹特征提取是指纹识别系统的核心任务, 目

标是从原始图像中稳定提取脊线结构、纹理特征和细节点信息。传统方法在低质量、噪声和局部缺损指纹场景下存在明显局限, 而近年来深度学习在指纹增强、恢复和细节点检测方面取得突破。

在指纹增强与恢复方面, Shi 等人(2021)提出了基于深度网络的婴幼儿指纹超分辨率方法; Zhu 等人(2023)利用GAN进行现场指纹增强; Jia 等人(2024)通过自编码器与Transformer恢复不完整指纹; Murshed 等人(2024)提出了适用于旋转指纹的分割方法。在细节点与质量建模方面, Feng 等人(2023)融合局部与全局网络提升细节点定位精度; Terhöst 等人(2021)和 Mulay 等人(2024)分别从质量评估与真实特征点构建角度增强指纹特征可靠性。

此外, 针对高分辨率指纹中的汗孔特征, Ali 等人(2021)和 Liu 等人(2022)分别提出了基于CNN的汗孔检测与联合重建方法; Duan 等人(2023)和 Bonacim 等人(2025)在指纹姿态估计与脊线计数方面取得了较高精度。总体来看, 深度学习显著提升了指纹特征提取对复杂场景的适应能力, 但在泛化性、可解释性及异常指纹鲁棒性方面仍需进一步研究。

1.3.2 指纹匹配

指纹识别的核心在于构建鲁棒特征表示并实现高效匹配。随着数据库规模扩大和传感器多样化, 传统匹配方法在效率和性能上面临瓶颈, 深度学习方法在固定长度表示、密集特征匹配和多阶段检索方面展现出优势。

针对现场指纹识别, Gu 等人(2022)和 Wu 等人(2022)分别提出了多尺度固定长度表示和融合全局与局部信息的细节点表示; Grosz 等人(2023, 2024)通过多阶段搜索和注意力机制提升识别性能; Pan 等人(2024)和 Qiu 等人(2025)利用密集描述子和可解释多阶段匹配网络提高现场指纹匹配精度。针对部分指纹识别, Chen 等人(2022)、He 等人(2022)、Guan 等人(2024)和 Gao 等人(2025)通过注意力机制、多任务学习和校准策略提升了部分指纹验证性能。

在扭曲指纹识别方面, Guan 等人(2022, 2023)提出基于自参考网络的扭曲校正方法, 有效提升了扭曲场估计和匹配性能。总体来看, 指纹识别技术正由单一特征匹配向多粒度特征融合与深层语义建

模发展,但在跨设备识别效率、可解释性和隐私保护方面仍有提升空间。

1.3.3 指纹数据集构建

数据集是推动指纹识别发展的关键基础。Malhotra 等人(2023)、Liu 等人(2024)和 Kirchgasser 等人(2025)分别构建了多类型、大规模及跨传感器指纹数据集,为复杂场景研究提供了支撑。与此同时,合成指纹数据逐渐受到关注, Bahmani 等人(2021)、Engelsma 等人(2022)、Shoshan 等人(2024)和 Grosz 等人(2025)分别基于 GAN 和扩散模型生成可控、高保真的合成指纹,为数据扩展与隐私保护提供了新途径。

1.3.4 新模态指纹

随着采集方式多样化,非接触指纹、三维指纹及光学相干断层扫描(Optical Coherence Tomography, OCT)指纹逐渐成为研究热点。Grosz 等人(2021)、Tan 等人(2021)和 Parashis 等人(2025)在非接触与接触式指纹匹配方面取得进展;Cui 等人(2023)和 Dong 等人(2023, 2025)通过三维建模缓解透视扭曲并提升跨姿态识别性能。

在 OCT 指纹方面, Ding 等人(2022)、Liu 等人(2024)和 Miao 等人(2024, 2025)分别在指纹重建、增强和跨设备适应方面取得进展;ZJUT-EIFD 数据集(Sun 等, 2023)为内外部指纹联合研究提供了重要基准。总体而言,新模态指纹推动指纹识别从二维图像向三维结构和多模态融合演进,尽管仍面临采集效率和算法复杂度挑战,但在无接触和跨姿态识别方面展现出广阔前景。

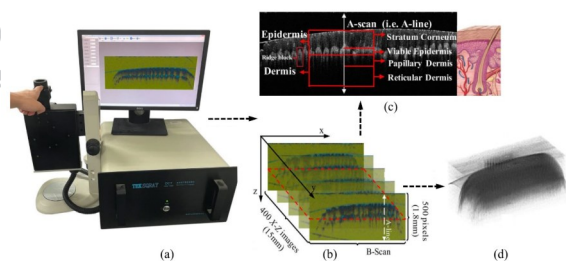


图6 OCT 指纹采集和重建过程(Liu 等, 2024)

Fig. 6 OCT Fingerprint acquisition and reconstruction

1.4 掌纹识别研究现状

自动掌纹识别研究最早由张大鹏教授于2000年左右在香港理工大学提出。经过二十余年的发展,掌纹识别技术已从传统特征工程方法逐步演进

至以深度学习为核心的技术体系,并在近十年取得突破性进展,推动了掌纹识别在实际场景中的大规模应用。

针对传统掌纹识别方法,已有多篇综述系统总结了相关研究进展,如 Kong 等(2009)、张大鹏等(2012)、钟德星等(2018)、费伦科等(2019, 2020)、Ungureanu 等(2020)、赵淑平等(2023)及李树一等(2024)。此外,孙哲南等(2021)在《生物特征识别学科发展报告》中对2021年之前的掌纹识别研究进行了系统总结,因此本节重点关注2021—2025年间的最新研究进展。

1.4.1 近年来的主要进展

近年来,随着深度学习在掌纹识别中的广泛应用,长期制约实际落地的关键问题逐步得到缓解,掌纹识别开始进入规模化应用阶段,且通常与掌静脉识别联合使用。如亚马逊公司于2020年推出的 Amazon One 产品,以及腾讯于2023年发布的刷掌支付系统,均表明掌纹识别已具备成熟的工程应用条件。

在算法层面,掌纹图像生成、感兴趣区域(Region of Interest, ROI)提取和识别方法均取得显著进展。掌纹生成技术被广泛用于缓解数据规模受限与隐私风险问题;基于深度学习的 ROI 提取方法逐步成熟;同时,融合传统特征与深度特征的识别算法不断刷新识别性能。此外,在图像质量评估、图像增强、安全与隐私保护以及多模态识别等方面亦取得了持续进展。



亚马逊 Amazon One

腾讯刷掌支付产品

图7 亚马逊公司和腾讯公司的刷掌支付产品

Fig. 7 Amazon and Tencent's palmprint payment products

1.4.2 掌纹采集与对齐

针对非接触式掌纹采集中的对齐难题,张大鹏团队提出了一系列代表性方法。Liang 等(2022)通过硬件标定与几何建模实现双模态掌纹与掌静脉图像对齐;Fan 等(2025)提出 ERAlign 方法,利用多距离动态注册与旋转不变 ROI 对齐策略,实现了非接

触掌纹的高精度对齐,显著提升了识别鲁棒性。

1.4.3 掌纹ROI提取

掌纹ROI提取是识别系统的关键步骤。传统方法依赖指谷关键点构建坐标系,近年来逐步被深度学习方法取代。Liu等(2022)和Liang等(2023)将ROI提取转化为关键点回归问题,通过轻量级网络和弱监督策略提升复杂场景下的鲁棒性。Su等(2024)和Chai等(2025)进一步摆脱对指谷点的依赖,将ROI提取建模为目标检测或分割问题,显著提升了非约束环境下的成功率。Chen等(2025)提出基于智能体运动控制的ROI提取方法,在保证精度的同时降低了计算复杂度。

1.4.4 掌纹图像质量评估与增强

在质量评估方面,Sun等(2021,2022)、Zou等(2023)和Zhang等(2024)分别从监督、无监督及几何感知角度提出了无参考掌纹图像质量评估方法,有效服务于非接触式掌纹识别流程。在图像增强方面,Zhou等(2025)和Wang等(2024,2025)通过U-Net、混合注意力和状态空间模型等技术,显著提升了低光照、低分辨率及噪声掌纹图像的质量。

1.4.5 掌纹图像生成与数据扩增

针对掌纹数据规模不足问题,近年来涌现出多种身份可控的掌纹生成方法。Zhao等(2022)与Shen等(2023)提出基于贝塞尔曲线和GAN的伪掌纹生成方法;Jin等(2024,2025)通过掌线能量图和扩散模型提出PCE-Palm与Diff-Palm,实现身份一致性与类内多样性的精确平衡;Zou等(2025)和Tang等(2025)进一步通过身份注入和条件扩散模型实现高真实度、可控生成。此外,Jin等(2025)提出对抗式掌纹数据增强框架,用于提升模型在复杂场景下的鲁棒性。

1.4.6 掌纹识别算法

在识别算法方面,研究者从传统方法与深度学习两个方向持续推进。传统方法如Yang等(2020)、Zhao等(2020)、Jing等(2022)和Fan等(2024)通过方向特征、稀疏建模与结构编码提升识别鲁棒性。近年来,深度学习方法成为主流,Zhang等(2020)、Feng等(2023)、Shao等(2025)和Zhao等(2024)从局部证据融合、多视图建模和噪声标签校正等角度提升非接触掌纹识别性能。

此外,结合Gabor滤波器与深度网络的混合方法(Liang等,2021;Yang等,2023a,2023b;Fan等,

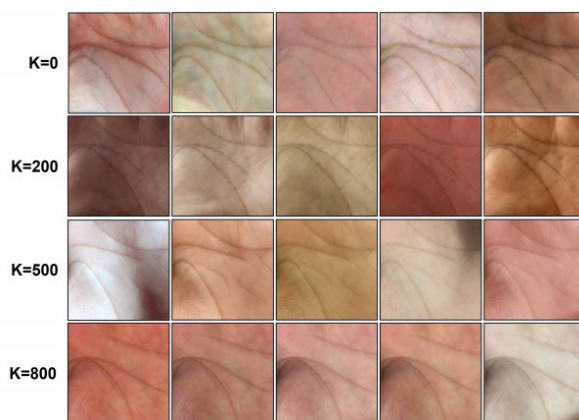


图8 Diff-Palm采用K步共享噪声采样生成数据集

Fig. 8 Diff-Palm uses K-step shared noise sampling to generate palmprints

2024;Liu等,2025)在纹理建模与对齐方面表现突出。针对非约束、跨设备、跨数据集与跨光谱场景,Shen等(2022)、Shao等(2021a,2021b,2023,2024)、Du等(2020)、Fei等(2021,2023a)和Ruan等(2024)等提出了多种领域适应与生成式解决方案。针对少样本与轻量化需求,Jing等(2023)、Fei等(2020,2023b)和Jia等(2022)提出了有效方法。

在大规模识别方面,Shao等(2021d)和Zhong等(2025)通过哈希学习与统一方向建模,显著提升了掌纹识别在大规模场景下的效率与鲁棒性。

1.4.7 手部多模态识别

近年来,掌纹与掌静脉等多模态融合成为重要发展方向。Fan等(2024)构建了大规模手部多模态数据库,并通过自适应融合策略在高效率条件下实现极低等错误率;Qiao等(2025)进一步提出完整的多模态识别系统,通过特征解耦与融合显著提升识别性能。

1.5 指掌静脉识别研究现状

指掌静脉识别技术基于血红蛋白对近红外光吸收特性的差异成像原理,使静脉纹路在成像中呈现为深色结构。该类技术具有稳定性高、抗仿冒性强、支持非接触采集与天然活体检测等优势,在高安全等级身份认证场景中具有重要应用价值。随着深度学习理论和算力条件的成熟,近年来指掌静脉识别研究已全面转向深度学习范式,研究重点涵盖数据获取、特征表达与场景适应等方面。

1.5.1 更广泛的数据获取

受采集设备、隐私政策及生理特征不可见性的
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限制,指掌静脉识别长期面临数据规模不足问题。近年来研究呈现“真实数据扩展+合成数据增强”并行的发展趋势。

在指静脉真实数据方面,研究逐步从受控采集转向多视角、全视图及三维建模。Zhao等(2024)构建了多视图指静脉数据库 THUMVFV-3V;Huang等(2024)提出基于镜面反射的全视图采集设备和 MFFV 数据集;Xu等(2022)和 Yang等(2021)分别构建了包含姿态变化与多视角信息的 3D 指静脉数据集 (SCUTLFMB-3DPVFFV、LFMB-3DFB)。此外, Ren等(2022)通过新型传感设备构建了 NUPT-FPV 数据集。

在合成与仿冒数据方面, Bhattacharjee等(2024)提出 Sweet 平台用于采集真实与呈现攻击样本;Wang等(2025)提出 FVeinSyn,实现了百万规模、具有丰富类内变化的指静脉合成数据。

针对掌静脉的真实数据, Lin等(2025)提供了 ROI 标注数据集;Luo等(2024)发布了在无约束和弱协作条件下采集的大规模掌静脉数据集 SCUT_PV_v1。在合成数据方面, Salazar等(2021)、Ou等(2022)和 Huang等(2024)分别从血管结构建模、GAN 分级生成和域自适应角度开展研究;Shang等(2025)提出 PVTtree 框架,通过 3D 血管树建模保证多视角几何一致性;Advein-AU(Qin等,2023a)通过对抗优化生成更具挑战性的样本。

1.5.2 更精准的特征表达

近年来,指掌静脉特征表达从单模态、单卷积特征向多尺度、全视图与跨域融合演进,并广泛引入 GAN、Transformer 与 Mamba 等新型架构。

在指静脉识别中, Noh等(2021)和 Choi等(2021)通过 GAN 提升低质量与异构数据下的识别性能;Meng等(2021)结合 ROI 与区域细节匹配缓解变形问题。Transformer 架构逐渐成为重要工具,如 FVT(Huang等,2022)和 Qin等(2023b)提出的局部注意力模型。FVFSNet(Huang等,2023)、FS-STMFPPV-Net(Abdullahi等,2023)及 FDT(Huang等,2025)则从空-频域融合、时序建模和冗余抑制等角度提升特征判别性。

在掌静脉识别中,研究一方面延续对传统特征的改进(Ananthi等,2022;李胜勋和黄靖,2023),另一方面不断优化深度网络结构。Jin等(2024)和 RSNet(Luo等,2025)通过大核卷积与多尺度聚合增

强全局特征;Qiao等(2025)引入精细语义注释实现全手掌的生物特征提取。Transformer 与 Mamba 结构亦逐步应用于掌静脉识别(Lu等,2024;Qin等,2023,2024)。

此外,小样本与生成式学习(Qin等,2021;Ma等,2023)、旋转鲁棒性建模(Lin等,2025)以及手背静脉识别(Cimen等,2021;Jiang等,2022;Lu等,2025)等方向也取得持续进展。

1.5.3 更稳健的场景适应

在实际应用中,指掌静脉识别面临光照变化、姿态多样及用户配合度低等挑战。为此,研究者从系统范式、ROI 提取、质量评估与形变校正等方面提升场景适应能力。

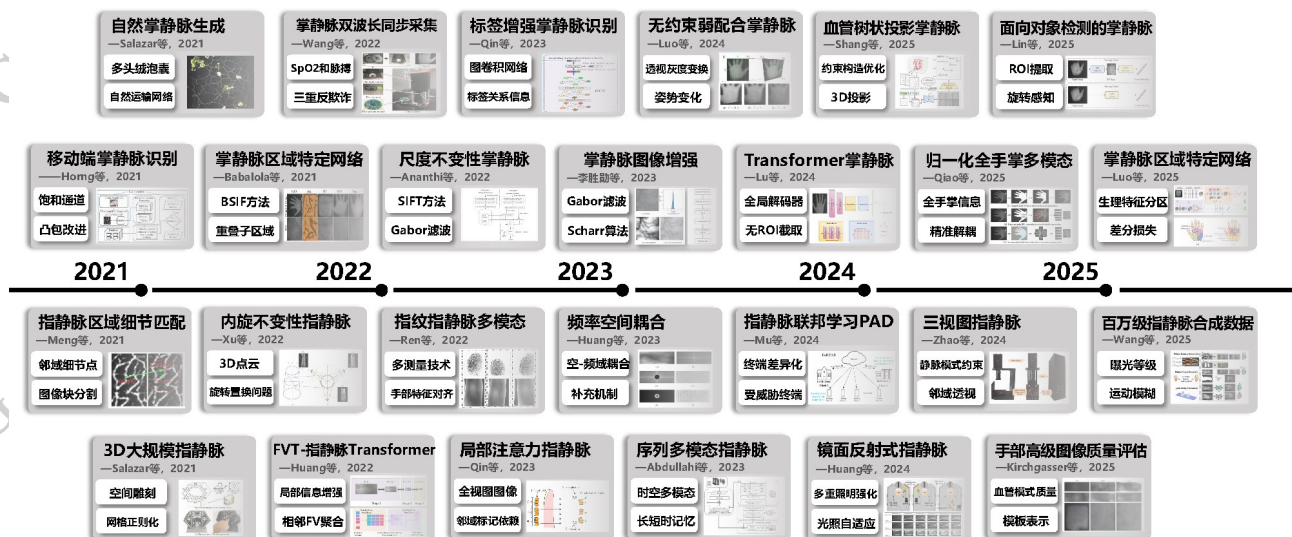
Luo等(2024)提出 on-the-fly 掌静脉识别范式,实现无约束和弱协作条件下的识别;Lin等(2024)提出的 KCNet 可实现户外环境下的鲁棒 ROI 提取;Chen等(2021)通过结合轻量级 CNN 与可解释 AI 解决多光谱适应问题。在质量评估与增强方面,Kirchgasser等(2025)提出通用质量度量标准;ILACS-LGOT(Kaveen等,2025)和 Ananthi等(2022)从对比度增强与多分辨率分析角度提升图像质量。

针对姿态变化引起的局部形变, Horng等(2022)提出凸包改进的 ROI 提取策略;MMD-filter(Kaveen等,2025)通过关键点统计过滤错误匹配,为非接触式高精度识别提供了保障。

行人重识别(PersonRe-identification, ReID)旨在跨摄像头视角匹配同一行人身份,是智能安防和智慧城市的重要基础能力。如图 10 所示,ReID 需要在跨相机、跨时间和跨空间条件下保持稳定判别。尽管基于卷积神经网络和 Transformer 的方法在标准数据集上取得显著进展,但多依赖场景封闭、设备同质和精细标注等理想假设,在真实城市环境中仍面临异构设备、光照变化、遮挡、远距离成像和频繁换装等挑战。

近年来,ReID 研究整体从“单模态、单场景、小模型”向“多模态、多平台、大模型”范式演进。一方面,数据形态由彩色图像扩展至红外(Wu等,2017)、文本(Li等,2017)、草图(Pang等,2018)、骨架(Rao等,2021)等多源模态,采集平台也从固定摄像头拓展至无人机和移动机器人(Zhang等,2024;Ye等,2024);另一方面,学习范式逐步向无监督、弱监督和终身自适应转变,以降低对大规模人工标注的依赖。

冯建江, 贾伟, 李琦, 崔哲, 赵才荣, 雷震, 王财勇, 康文雄, 于仕琪, 费伦科, 李晓白, 叶茫, 卫建泽, 曹始文, 孙士博, 谢天明, 郑伟诗, 杨鸿宇, 黄俊端, 黄迪, 孙哲南



1.6 行人重识别研究现状



图 10 行人重识别任务需求

Fig. 10 Requirements of the ReID task

与此同时, 视觉-语言预训练模型和提示学习推动 ReID 迈向统一多模态语义空间(Feng 等, 2025)。图 11 概括了目前 ReID 的六大主要研究方向。

1.6.1 学习范式类研究

图 12 展示了 ReID 的四类学习范式, 其中有监督 ReID 已形成以分类损失与度量损失联合优化为

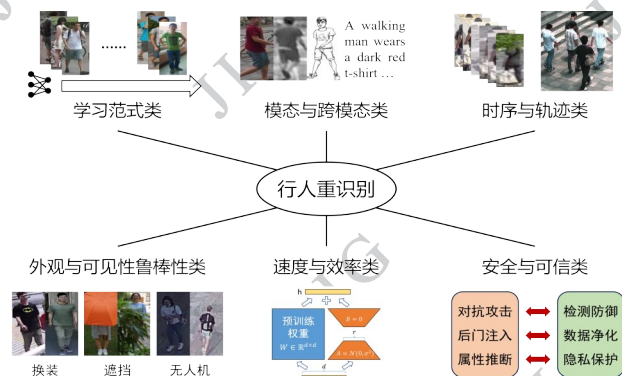


图 11 行人重识别主要研究方向

Fig. 11 Main research directions of ReID



图 12 学习范式视角下的行人重识别任务

Fig. 12 ReID tasks from the perspective of learning paradigms

核心的成熟框架(郑等, 2018; Luo 等, 2019)。BagofTricks(Luo 等, 2019)系统整合常用策略, 构建了强基线。随后研究从全局特征逐步发展到多粒度与局部结构建模, 如 PCB(Sun 等, 2018)和 MGN

(Wang 等, 2018), 并通过注意力机制和跨图关系建模提升细粒度判别能力(Chen 等, 2019; Zhang 等, 2020; Zhu 等, 2022)。随着 Transformer 的引入, TransReID(He 等, 2021)及其改进方法通过自注意力实现全局建模, 并结合局部校准和部件对齐提升鲁棒性(Zhang 等, 2021; Zhu 等, 2023)。在视觉语言预训练背景下, ReID 进一步引入语义先验, 通过 CLIP 对齐、提示学习和属性引导, 使身份表征更加可解释(Li 等, 2023; Yang 等, 2024; Yu 等, 2025)。此外, 基于大规模未标注行人数据的自监督预训练, 如 LUPerson(Fu 等, 2021)和 PASS(Zhu 等, 2022), 显著提升了特征的可迁移性。

由于真实场景中精细标注成本高昂, 无监督与弱监督 ReID 成为重要研究方向。主流方法采用“聚类生成伪标签+对比学习”的迭代框架(Ge 等, 2020; Dai 等, 2022), 并通过簇结构一致性、跨相机分解和关系校正提升伪标签质量(Chen 等, 2021; Xuan 等, 2021; Li 等, 2024)。生成式方法利用 GAN 或扩散模型增强跨视角和跨模态一致性(Chen 等, 2021; Ho 等, 2020), 弱监督方法则在有限标注条件下联合相机内监督与跨相机关系挖掘, 取得接近有监督的性能(Zhu 等, 2021; Wu 等, 2023)。

面向长期运行系统, 终身学习 ReID 通过排序一致性蒸馏、原型与分布级回放以及域统计元学习, 在不访问或少访问历史数据的条件下实现知识保留与增量适应(Pu 等, 2021; Ge 等, 2022; Xu 等, 2024; Zhou 等, 2025)。与之相关的领域泛化 ReID 关注在未见目标域上的稳定性能, 通过归一化、风格建模、局部匹配和多源元学习缓解域偏移问题(Jin 等, 2020; Choi 等, 2021; Liao 等, 2020; Ni 等, 2022), 并逐步引入视觉语言模型以增强域不变性(Zhao 等, 2025)。



图 13 行人重识别中的不同模态

Fig. 13 Typical modalities in ReID

1.6.2 模态与跨模态类研究

随着应用场景拓展, ReID 已从单一 RGB 模态扩展至可见光-红外、文本、草图和骨架等多种模态, 如图 13 所示。跨模态 ReID 主要通过特征对齐、跨模态注意力或生成式模态补全缓解模态差异(Jiang 等, 2022; Zou 等, 2024; Wu 等, 2022)。多模态 ReID 则致力于构建统一语义空间, 通过深度融合和视觉语言预训练模型实现多模态协同(Chen 等, 2022; Wang 等, 2025; Zuo 等, 2025)。

文本检索行人任务进一步引入自然语言语义, 通过短语-区域对齐和提示调优提升对复杂描述的适应能力(Jing 等, 2020; Bai 等, 2023; Tan 等, 2024), 如图 14 所示。草图与骨架 ReID 利用结构先验, 在遮挡、换装和低照度场景中展现出优势(Pang 等, 2018; Rao 等, 2021; Geng 等, 2025)。

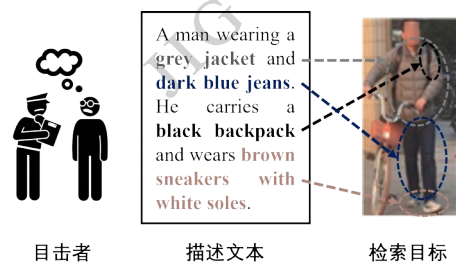


图 14 文本检索行人示例

Fig. 14 Example of text-based person search

1.6.3 时序与轨迹类研究

视频 ReID 通过建模时序信息缓解单帧噪声, 常采用 Transformer 与记忆机制实现时空聚合(Wang 等, 2021; Alsehaim 等, 2022)。群体 ReID 则利用图结构建模群体成员关系, 在成员变化和局部缺失条件下保持判别能力(Huang 等, 2019; Zhang 等, 2024)。随着检测、跟踪与 ReID 的一体化发展, 轨迹级约束和在线自训练逐渐成为实际部署的重要方向(Xie 等, 2021; Ye 等, 2024)。

1.6.4 外观与可见性鲁棒性类研究

真实场景中, 换装、遮挡和无人机场景是 ReID 的主要挑战, 如图 15 所示。针对换装问题, 研究通过衣物无关特征、生成式换装增强和多模态融合提升鲁棒性(Yang 等, 2019; Chen 等, 2021; Zeng 等, 2025)。针对遮挡, 显隐建模、局部关系推理和遮挡模拟训练被广泛采用(Miao 等, 2019; Wang 等, 2020; Gao 等, 2023)。在无人机 ReID 中, 视角校正、超分辨

冯建江, 贾伟, 李琦, 崔哲, 赵才荣, 雷震, 王财勇, 康文雄, 于仕琪, 费伦科, 李晓白, 叶茫, 卫建泽, 曹始文, 孙士博, 谢天明, 郑伟诗, 杨鸿宇, 黄俊端, 黄迪, 孙哲南

率恢复和空-地跨平台域对齐成为关键技术(Han 等,2024;Qu 等,2024)。



图 15 行人重识别中的外观与可见性挑战

Fig. 15 Appearance and visibility challenges in ReID

1.6.5 速度与效率类研究

面向大规模部署, ReID 研究逐渐关注模型压缩与高效检索。低秩分解、量化、知识蒸馏和轻量网络显著降低了计算与存储开销(Ye 等, 2018; Hu 等, 2022)。哈希学习、向量索引和重排序技术提升了大规模检索效率(Zhao 等, 2021; Rao 等, 2022)。多出口网络和动态计算策略在精度与实时性之间取得平衡, 推动 ReID 走向边缘部署(Nikhil 等, 2024)。

1.6.6 数据集与评测

为评估算法性能, ReID 通常采用累计匹配特性曲线和平均精度作为核心指标。数据集从早期单模态逐步扩展至跨模态、视频、换衣、遮挡、无人机和虚拟合成等多种场景, 如 Market-1501、MSMT17、SYSU-MM01、CUHK-PEDES、MARS 和 UAVHuman 等(Zheng 等, 2015; Wei 等, 2018; Wu 等, 2017; Li 等, 2017; Zheng 等, 2016; Li 等, 2021)。多样化数据集的出现显著提升了对真实场景泛化能力的评估深度。

1.6.7 未来发展趋势

总体来看, 行人重识别正从封闭实验环境迈向复杂、开放、长期运行的真实应用。未来研究需在泛化与终身适应、多模态与大模型融合、系统一体化、

隐私保护以及可解释与可靠性等方面协同推进, 使 ReID 在保证性能的同时具备可部署、可审计和可信赖的工程属性。

1.7 步态识别研究现状

步态识别是一类利用个体行走过程中表现出的运动模式及相关静态外观特征, 实现远距离、非接触式身份识别的生物特征技术。相较于指纹、虹膜等接触式模态, 步态识别可在远距离、低分辨率及低配合度条件下完成识别, 在视频监控、公共安全和智能交通等场景中具有独特优势。现代深度步态识别方法通常通过端到端学习, 将周期性运动信息与体型比例、肢体结构及外观轮廓等静态线索联合编码为判别性表征, 在复杂协变量条件下保持较好的区分能力(Shen 等, 2024)。

1.7.1 步态识别的发展脉络

过去二十余年的步态识别研究大致经历了三个阶段: 基于人工设计特征的早期阶段、基于深度表征学习的阶段, 以及面向真实场景与大模型融合的新阶段。早期方法多依赖步态能量图等模板特征, 并结合主成分分析、线性判别分析等降维与分类方法完成识别(Han 和 Bhanu, 2006), 主要在 CASIA-B、

OU-ISIR 等受控数据集上评估(Yu 等, 2006; Maki-hara 等, 2012; Takemura 等, 2018)。

随着深度学习的发展,研究者引入二维与三维卷积网络以及集合式网络结构,对步态序列进行时空建模(Wolf 等, 2016; Chao 等, 2019)。此后,方法逐步从整体表征转向局部结构建模,如 GaitPart(Fan 等, 2020)、GaitGL(Lin 等, 2022)和 GaitParsing(Wang 等, 2023),在受控数据集上取得了接近饱和的识别精度。

近年来,研究重点逐渐转向真实场景步态识别。Gait3D、GREW 和 CCGR 等数据集系统刻画了复杂环境下的步态变化,为算法泛化能力评估提供了重要基准(Zheng 等, 2022; Zhu 等, 2021; Zou 等, 2024)。OpenGait 框架进一步对主流方法进行统一复现与比较,揭示了跨数据集迁移和真实场景中的性能瓶颈(Fan 等, 2025)。

1.7.2 基于模型与基于表征的特征范式

从特征建模角度看,步态识别方法可分为基于模型和基于表征两类。基于模型的方法通过骨架、三维人体网格或可穿戴传感器显式建模人体结构与运动学特征,具有较强的物理可解释性和跨视角鲁棒性(Ailisto 等, 2005; Zheng 等, 2022),但依赖高质量姿态估计,计算与部署成本较高。

基于表征的方法则直接从剪影、RGB 帧、人体解析图或光流中学习步态特征(Shen 等, 2024; Fan 等, 2023),在信息表达和实际性能上更具优势。随着三维卷积、集合式网络与 Transformer 架构的发展,该类方法在受控和部分真实场景中取得了显著优于基于模型方法的性能。然而,其特征往往同时编码外观与场景因素,对服饰变化和遮挡较为敏感。CCGR 数据集系统分析了多种协变量对识别性能的影响,并提出利用更具语义的中间表征缓解非步态因素干扰(Zou 等, 2024)。总体来看,模型化先验与外观表征的融合已成为重要发展方向。

1.7.3 步态识别的最新进展

近期研究重点逐渐转向大规模未标注数据与通用视觉/语言大模型的利用。GaitLU-1M 基准通过自监督对比学习,在百万级未标注步态数据上预训练通用步态编码器,显著提升下游任务的泛化能力(Fan 等, 2023)。在通用视觉大模型方面, BigGait 利用 DINOv2 等预训练模型提取多层特征,并通过轻量级步态表征提取器过滤背景与服饰噪声,实现了与

专用网络相当的性能(Ye 等, 2024)。BiggerGait 进一步挖掘不同层级特征的互补性,在视角变化和跨数据集场景下表现更为稳健(Ye 等, 2025)。

在多模态方向, Jin 等(2025)融合剪影、光流与人体解析图等多种模态,提升复杂场景下的稳定性。GaitLLM 首次将大语言模型引入步态识别,通过“步态—语言”映射实现序列建模,在真实场景数据集上展现出良好的迁移能力(Yang 等, 2025)。

1.7.4 步态识别的发展趋势

未来步态识别的发展将主要体现在数据规模、学习范式和模型形态三个方面。大规模未标注视频、多模态与三维步态数据将持续推动算法泛化能力提升(Fan 等, 2023; Zou 等, 2024; Zheng 等, 2022)。在学习范式上,自监督与大模型特征迁移将与监督学习长期共存,并逐步形成统一的“以人为中心”的基础模型。模型层面,融合视觉大模型、语言模型与三维表示的统一步态与行为建模框架,正在为身份识别、轨迹预测和行为理解提供新的可能性(Yang 等, 2025; Shen 等, 2023)。

1.7.5 步态识别与行人重识别的关系

步态识别与行人重识别在目标和数据形态上高度相关。二者均旨在跨摄像机关联同一行人,但 ReID 更侧重静态外观,而步态识别强调长期运动模式(Li 等, 2023)。随着视频 ReID 的发展,两类任务在时序建模和特征学习上逐渐趋同。CCPG 和 CCGR 等数据集在统一协议下对比了 ReID 与步态方法在服饰变化条件下的表现,表明二者具有明显互补性(Li 等, 2023; Zou 等, 2024)。随着检测、跟踪与识别一体化系统的发展,未来行人分析系统有望在统一框架下融合外观与步态信息,形成面向“人”的统一身份识别范式(Fan 等, 2025; Yang 等, 2025)。

2 生物特征识别的安全

生物特征识别技术在多领域广泛部署,其数字身份认证核心入口的安全性愈发突出。当前生物识别系统的攻击手段持续升级,已从单一物理呈现攻击,延伸至生成式 AI 驱动的数字伪造、对抗性扰动及跨域混合劫持,传统封闭集防御算法难以应对这类高保真、未知类型攻击,泛化性面临严峻挑战。

本章系统综述生物特征识别安全攻防前沿,涵盖人脸、虹膜等核心模态,剖析各模态在物理攻击应

对、数字伪造取证、对抗防御及隐私保护等方面的关键进展,重点阐述防御范式从数据驱动特征比对向因果推理、多模态大模型辅助等方向的演进逻辑,探讨开放环境下下一代高鲁棒、可解释、隐私合规的生物特征识别安全体系构建路径。

2.1 人脸识别安全

人脸识别系统广泛部署后,安全威胁已从单一物理呈现,演进为跨物理空间与数字链路的复合挑战,防御技术也从独立分治转向统一建模。物理采集端,呈现攻击检测(Presentation Attack Detection, PAD)是第一道防线,核心目标是鉴别人脸图像源自真实生物体,还是打印照片、3D面具等物理伪造媒介,防范成像前的物理载体攻击。

信号进入传输链路后,攻击转为隐蔽的图像劫持与数字注入,人脸深度伪造检测(又称人脸伪造取证)发挥关键作用,鉴别图像为真实采集或深度生成算法合成,防御多种深度伪造形式。针对两端攻击并存态势,人脸物理与数字攻击统一检测(Unified Face Attack Detection, UAD)技术应运而生,旨在构建通用模型,同步防御两类攻击,解决其特征分布差异难题,应对全链路混合攻击。

2.1.1 呈现攻击检测

从检测模式演变来看,早期PAD采用“主动配合式”,需用户完成眨眼(Pan等,2007)、头部转动(Kollreider等,2007)等动作验证活体;后续转向无需用户配合的“被动检测”。深度学习前,被动检测依赖手工特征,如Määttä等人(2011)用LBP分析微纹理,Wen等人(2015)基于图像失真检测,Boulkenafet等人(2016)提取多颜色空间特征提升鲁棒性,另有研究利用时序特征捕捉攻击异常。

深度学习爆发后,CNN成为主流,Yang等人(2014)率先将其引入PAD领域。后续研究引入辅助监督信号提取精细活体特征,如Atoum等人(2017)用全卷积网络预测人脸深度图,Liu等人(2018)结合深度信息与生理信号,像素级二进制掩码监督也被广泛应用以提升局部攻击检测能力。

为解决模型泛化能力不足问题,研究者在零样本学习和域泛化领域成果显著。零样本攻击检测中,Liu等人(2019)用深度树网络探索欺诈样本语义子群,Qin等人(2020)引入元学习实现模型快速适应新攻击;跨域泛化方面,Jia等人(2020)通过不对称对抗学习提升未知域鲁棒性,Jiang等人(2024)提

出开放集单域泛化框架,拓展PAD应用边界。

多模态大模型推动PAD向视觉-语言协同表征转变,Liu等人(2024)利用CLIP模型文本提示能力实现跨域检测;Jiang等人(2025)提出知识图谱提示学习框架,融入专家先验知识并结合因果图理论,提升对高保真3D面具的检测鲁棒性。

2.1.2 人脸深度伪造检测

人脸深度伪造检测早期以CNN数据驱动有监督学习为主,Rössler等人(2019)构建FaceForensics++数据集确立基础框架,但泛化性不足。后续研究转向物理伪影与特征优化:Afchar等人(2018)用MesoNet分析介观噪声;Li等人(2020)提出FaceX-ray聚焦人脸融合边界;Qian等人(2020)用F3-Net挖掘频域异常;Zhao等人(2021)引入多头注意力增强判别力。

检测对象转向动态视频后,研究聚焦时空一致性与语义特征:Haliassos等人(2021)用LipForensics校验唇形与语音一致性;Zheng等人(2021)用FTCN捕捉时序运动异常;Haliassos等人(2022)提出RealForensics,以单类分类和自监督学习提升普适性。

应对零样本攻击与新型生成技术,相关策略逐步兴起:Shiohara和Yamasaki(2022)用自混合图像(SBI)策略生成合成数据提升泛化;Wang等人(2023)用DIRE算法实现扩散模型生成内容溯源;Zhang等人(2024)引入语言模态,推动多模态协同检测演进。

2.1.3 针对物理与数字攻击的统一检测模型

早期物理与数字伪造检测独立建模导致泛化不足,研究者提出针对性方案:Thakral等人(2023)用PhygitNet减少协变量偏移;Deb等人(2023)用UniFAD通过多任务学习获取联合表示;Fang等人(2024)构建UniAttackData数据集并提出知识挖掘框架;Liu等人(2025)推出超大规模UniAttackData+数据集。

当前主流方法利用视觉-语言模型与混合专家系统处理特征异构性:Zou等人(2024)用LaSoftMoE CLIP适配稀疏特征空间;Xie等人(2025)用SUEDE框架捕捉通用与特定攻击特征;Liu等人(2025)提出分层提示微调,Li等人(2025)用FA3-CLIP增强统一检测能力。

为提升未知攻击与跨域泛化性能,研究者引入人类推理与文本辅助:Jiang等人(2025)用GRPO策

略激发多模态大模型推理能力;Tan 等人(2025)构建 Veritas 框架,通过模式感知推理增强泛化表现。

如何进一步融合物理与数字攻击的异构特征,以及如何利用大语言模型的逻辑推理能力解决黑盒决策问题,仍然是未来值得关注的研究方向。探索更加通用、鲁棒且具备可解释性的统一检测模型,将是人脸安全领域的重要发展趋势。

2.2 虹膜识别安全

虹膜活体检测是虹膜识别系统的关键安全保障,核心是通过分析虹膜生理、动态或纹理特征,判别样本是否来自活体眼球,抵御伪造假体的攻击干扰(王等,2024)。随着虹膜识别在金融、安防、智能终端等场景普及,打印虹膜、屏显视频、3D 义眼及 GAN 合成虹膜等攻击手段不断升级,带来身份冒用等风险,因此具备泛化性、实时性的活体检测技术成为核心需求。

主流虹膜假体分为三类:物理假体(打印虹膜、义眼、纹理隐形眼镜等)、动态假体(屏显设备播放虹膜视频)、数字假体(GAN 等生成的高逼真合成虹膜),尸体及病变虹膜也属特殊假体。

目前主流检测方法为软件类,结合 CNN(Tapia 等,2022;Gautam 等,2022)、ViT(Sharma 等,2025)等深度学习模型,引入对抗学习(Yadav 等,2021;Pal 等,2025)、注意力机制(Chen 等,2021;Fang 等,2021;Jaswal 等,2024;Wang 等,2026)等策略提升性能。Dhar 等人(2022)提出多任务学习框架同时进行虹膜活体检测和虹膜识别,结合知识蒸馏实现单模型多任务集成,降低了计算复杂度。

虹膜假体数据匮乏制约模型发展,Yadav 等人(2025)提出 MID-StyleGAN 框架生成多域合成数据, Kim 等人(2025)提出 PGLAV-GAN 提升数据逼真度, Boyd 等人(2023)提出算法集成方案,均为解决数据问题提供思路。

综上,现有算法在跨领域、跨攻击类型等开放场景下泛化性有限,提升此类场景下的泛化性能是未来核心研究方向。

2.3 指纹识别安全

随着指纹识别在多场景广泛应用,攻击检测成为保障系统安全的关键。近年来,基于深度学习的指纹防伪方法多从全局-局部特征、跨传感器、手指内部结构等方向展开,不断提升真实与攻击指纹的区分能力。

Liu 等人(2021)提出全局-局部模型攻击检测方法,误检率 1.0% 时,平均分类错误率 2.28%、真检率 91.19%,优于现有方法约 10%。Micheletto 等人(2021)将攻击检测融入指纹验证系统,通过概率建模模拟器关联两阶段受试者操作特性曲线,提升整体验证性能。Wijewardena 等人(2022)评估发现,深度指纹模板比细节模板更抗重建攻击,其反转生成图像对黑盒攻击抵抗力更强。Fei 等人(2024)针对指纹伪影梯度特征,提出方向中心差分卷积层,整合脊线与边缘处理特征。Reza 等人(2025)提出跨传感器框架,利用活体分数预测器增强局部特征,缓解过拟合。

合成数据方面,Grosz 等人(2022)提出 SpoofGAN,合成指纹数据仅需 25% 原始真实数据,即可使检测性能达标。Wone 等人(2025)的合成指纹欺骗方案,生成图像匹配性能接近真实指纹,多数材料注入攻击成功率达 50%。

Sun 等人(2023)针对 OCT 指纹攻击,结合外部指纹、内部指纹和皮下汗孔特征实现精准区分;Liu 等人(2024)提出小波记忆增强自动编码器,融合频域信息,有效解决非接触指纹攻击检测问题。

2.4 掌纹识别安全

掌纹识别安全核心是构建可信体系,抵御外部攻击、保护用户隐私,防御分三层:感知层用活体检测防范打印图像、3D 假手等物理攻击;算法层增强模型鲁棒性,抵御误导决策的对抗攻击;数据层通过可撤销模板、加密等技术,保障泄露的生物模板无法还原,保护隐私。

2.4.1 掌纹识别呈现攻击与检测

掌纹识别攻击检测的首要目标是防御“呈现攻击”——攻击者在传感器端提交伪造生物特征样本的欺骗行为。此类攻击门槛低、威胁直接,如高分辨率二维伪造(早期欺骗接受率高达 79.8%)和硅胶、3D 打印立体假手,均对系统构成严重挑战。初期防御主要分为单模态掌纹图像深度分析与多模态生物特征融合两大路径。

单模态防御通过挖掘真伪样本的细微差异实现检测:Yao 等人(2022)构建大规模掌纹攻击数据集,提出域泛化防伪方法,提升对未知伪造方式的泛化能力;Ren 等人(2024)提出频域特征防伪方法(FES),通过离散余弦变换、特征增强及通道筛选实现分类;Liu 等人(2025)提出 HFSRA 模型,借助双模

块引导模型聚焦高频关键区分区域,提升检测性能。

多模态防御依托掌静脉活体特性,融合掌纹与掌静脉特征。例如,Fan等人(2024)设计融合系统,同步采集掌纹与近红外掌静脉图像判断活体;Wang等人(2024)通过双波长系统提取静态特征与动态生理信号,构建反欺诈模型。目前,在实际应用的掌纹识别系统中,如微信“刷掌”与亚马逊 Amazon One 等支付系统,均采用可见光与近红外摄像头并行采集掌纹与掌静脉图像,通过融合这两种模态的特征,实现了高效的活体检测与反欺诈验证。

2.4.2 掌纹对抗攻击与防御

除传感器端物理攻击外,掌纹识别系统正面临更严峻的“算法与模型级”高级威胁,此类攻击直指识别算法核心:Zhu等人(2023)通过在特征空间添加细微扰动生成对抗样本,质疑模型鲁棒性;Yang等人(2023)利用风格迁移等技术,仅凭泄露模板即可合成高仿真伪造掌纹,绕过传统活体防御。此类攻击还会引发连锁隐私危机,Yang等(2023)揭示,单一数据库泄露的模板可能推导出用户在其他系统的关联模板,导致生物特征“连锁泄露”,扩大隐私风险。

综上,“算法与模型级”攻防超越实体伪造防范,针对识别核心流程发起攻击,其研究可揭示系统脆弱性,驱动更坚固的识别算法、异常检测机制及隐私保护模板方案研发,全面提升掌纹识别系统安全水平。

2.4.3 掌纹隐私保护

掌纹识别隐私保护的核心是应对“数据层攻击”,确保生物特征模板在存储、传输、使用全过程安全,即便泄露也无法逆向还原或关联滥用,当前研究主要依托模板保护技术与隐私计算框架构建纵深防护体系。

传统隐私保护以可撤销与加密模板技术为核心,通过不可逆变换生成受保护模板,泄露后可快速重置。Leng等人(2011)引入二维掌纹相位作为可撤销模板,结合双重绑定机制增强安全性;Leng等人(2012)进一步提出 PalmHash Code 编码框架,优化隐私与实用性平衡。Liu等人(2024)的 PalmSec-Match 方案从原始掌纹提取密钥,通过多步骤加密实现隐私保护,已满足国际标准。

随着协作计算需求的增长,基于联邦学习的分布式隐私计算框架已成为掌纹识别隐私保护的前沿

方向。该方向秉持“数据不动模型动”理念,避免集中泄露。Cui等人(2024)将其应用于移动设备,实现协同训练;Zhang等人(2025)提出自适应框架,解决数据分布不均问题;Shao等人(2023)提出联邦度量学习,适配异构客户端,推动技术实用化。

综上,掌纹隐私保护正从单点静态加密向动态分布式范式演进,未来将融合密码学与机器学习,实现数据“可用不可见”,构建兼顾性能、安全与隐私的可信系统。

2.5 静脉识别安全

掌指静脉识别算法的性能被推向新高的同时,其安全边界也面临着前所未有的挑战。识别模型的黑盒特性催生了比传统伪造更为隐蔽和强大的攻击手段。本节将从掌指静脉的呈现攻击、对抗攻击和模板保护方面展开。

2.5.1 新型呈现攻击与检测

尽管传统观念认为静脉血管的活体属性阻断了大多数伪造的可能,但很多针对静脉的新型呈现攻击方法仍可突破识别系统,其手段不断升级,已从简单的纸张打印、电子屏幕重放,演进为基于 GAN 的合成攻击以及融合物理属性的高保真伪造,迫使防御机制向多模态活体检测与频域深度分析转型。

在高保真攻击样本的生成方面,攻击样本的逼真度直接决定了防御系统的鲁棒性上限。为了解决攻击数据匮乏的问题,Vorderleitner等人(2023)利用 GAN 的 I2I 翻译技术合成跨域攻击样本。Wang等人(2024)则关注物理成像机制,根据实际手部与其捕获图像之间由非均匀照明引起的亮度分布差异,通过建模和理论分析有效解决光照问题,从而生成了更具欺骗性的逼真样本。

面对日益精进的攻击,基于硬件和细节特征的活体检测成为第一道防线。Wang等人(2022)提出双波长采集系统,融合静态纹理与动态生理特征区分活体;图像纹理分析中,Schuiki等人(2022)通过分数级融合提升检测准确率,Ashari等人(2021)设计多尺度直方图捕捉伪造痕迹,此外 Ashari等人(2023)提出基于块方差的评估方法。针对 AI 深度伪造,Kim等人(2025)提出 FGFNet 在频域捕捉攻击伪影,Hafner等人(2025)实现跨传感器/模态检测,Mu等人(2024)提出联邦学习方法,在保护数据隐私的同时提升防御性能。

2.5.2 新型对抗性攻击

对抗性攻击代表了一个全新的、更为严峻的威胁维度。其核心在于通过对输入图像添加人眼难以察觉的微小扰动,恶意诱导深度模型做出错误判断。这种攻击直接威胁模型的核心决策机制,使得传统的活体检测手段往往难以奏效。

针对对抗样本的生成与攻击机制,研究者正致力于探索深度模型在特征空间的盲区。Yang等人(2024)设计双路径网络解耦特征,生成高逼真对抗图像;Nguyen等人(2023)结合进化算法与WGAN-GP验证通用攻击的威胁;Kim等人(2024)提出DCS-GAN生成精细假静脉图像,为防御训练提供数据。

面对隐蔽的对抗扰动,防御范式正从被动的检测转向主动的净化与鲁棒性学习。Wu等人(2023)提出AdCL框架学习稳健特征;Li等人(2023)的VeinGuard框架可清除恶意扰动;Fei等人(2025)通过重建网络分离对抗噪声与静脉纹理;Kim等人(2022)结合SVM集成与锐度感知最小化,提升模型对未知攻击的泛化性。

2.5.3 模板保护和密钥系统

原始生物特征一旦泄露将面临永久性失效的风险,因此,构建具有可撤销性和不可逆性的安全模板成为研究热点。可取消生物特征的核心理念在于存储经过变换的特征而非原始特征,当模板受损时,可以通过更改变换参数撤销旧模板并重新生成。在身份验证过程中,系统沿用与注册阶段相同的特征提取和生成逻辑进行比对。

在加密算法与密钥生成机制方面,研究者致力于将生物特征与现代密码学深度融合,以实现高安全性的密钥绑定与生成。Ren等人(2021)将RSA应用于静脉图像加密;Gizachew等人(2025)提出后量子安全的密钥生成方法;Xie等人(2025)通过动态绑定密钥抵御暴力破解;Nayar等人(2021)基于图论实现模板保护。

混沌理论因其对初值的极端敏感性和伪随机性,被广泛用于特征的置乱与混淆。Shao等人(2022)通过混沌映射隐藏静脉信息;Khan等人(2024)将混沌机制引入深度网络,实现端到端的特征保护。

在不可逆变换与可撤销模板构建方面,重点在于设计无法逆向重构原始特征的变换函数。Li等人(2025)提出非线性散列方法,Abdullahi等人(2023)

通过向量置换破坏特征相关性,Aherrahrou等人(2023)引入局部相异图实现特征域保护,Wang等人(2024)提出CFExpressRoute网络实现模板的不可链接性与可撤销性。

此外,多模态融合与几何特征的挖掘为模板保护提供了更稳固的基石。Lee等人(2024)利用掌静脉和掌纹之间的几何关系,提取跨模态交点作为稳定特征。El-Rahiem等人(2022)提出了基于心电图和静脉的深度融合系统,Singla等人(2026)则通过特征约简和距离矩阵进一步确保了认证过程的隐私性。

2.6 行人重识别中的安全可信问题

在真实部署中,ReID系统不仅追求高精度,更必须在开放环境下具备“可攻可防、可审可控”的可靠性与合规性。围绕这一目标,当前研究主要从对抗攻击与检测/防御、后门(触发器)投毒与净化、成员/属性推断等隐私风险量化,以及隐私保护式学习(脱敏、联邦、合成数据与新型传感)等方面展开。

对抗攻击研究从“分类式对抗”转向检索排序干预,深度误排序攻击以优化检索排名为目标,提升了物理场景可实施性(Wang等,2020);距离度量相关研究将ReID视作度量学习系统,探索了早期防御思路(Bai等,2020)。跨模态场景下,可见光-红外ReID催生了专属攻击框架与策略(Yang等,2024),基于成像机理的颜色扰动攻击搭配联合防御方案,工程可行性较强(Gong等,2022)。上线系统的防御则采用多专家对抗检测方法,可作为外接模块识别攻击样本,无需改动底层模型(Wang等,2021)。

后门攻击因ReID的开放集检索特性,触发器设计从固定标签绑定转向开放身份场景,动态隐形后门通过嵌入语义特征实现隐蔽且跨身份泛化的攻击(Sun等,2023),对应的防御需在无固定类别标签的前提下,识别并削弱触发器与检索结果的异常关联。

成员与属性推断研究聚焦相似度空间的隐私泄露风险度量,ReID-leak以成对相似度分布偏移为切入点,定量评估成员隐私泄露风险(Gao等,2023),也为其他隐私风险评估提供了统计视角。

在隐私保护式学习与系统落地层面,工作重点转向“在保证任务可用性的前提下抑制可逆性与滥用风险”。在图像层面,可逆匿名化与身份特定密钥加密框架能够生成可用于检索的匿名全身图像,并通过身份密钥控制的加密-解密过程限制原始外观

恢复的可行性,同时分析并缓解匿名化模型本身被当作攻击工具反向恢复身份的潜在风险(Shen等, 2024)。身份平移则利用生成模型的插值性,将每个人映射到新的“伪身份”,在保留样本间相对身份关系的同时移除绝对身份信息,从而在隐私保护与 ReID 可用性之间取得更平衡的折中(Dou等, 2022)。PixelFade(Zhang等, 2024)则通过噪声引导的渐进替换策略,将行人图像迭代优化为近似高斯噪声的外观,使恢复模型难以重建原图,同时借助特征约束维持对授权 ReID 模型的判别性。

训练范式上,联邦式 ReID 针对非独立同分布数据的性能问题,提出了动态调整聚合权重等解决策略(Zhuang等, 2020; Wu等, 2020);数据供给依托目标域感知的合成数据生成管线缓解隐私与标注压力(Chen等, 2022);新型传感则引入事件相机,既实现了基于事件流的有效识别(Wang等, 2026),又通过扰动事件流降低了隐私回溯风险(Ahmad等, 2023)。

总体而言,安全可信 ReID 研究已从早期单一方案,发展为覆盖攻击建模、风险量化、隐私友好训练的系统化框架,融合了精细化攻防、开放集隐私评估与多元联合防护手段。未来该领域的核心发展议题,是在保障安全性与合规性的同时,兼顾模型性能、计算成本与部署复杂度。

3 生物特征的其他应用

生物特征所具备的唯一性、稳定性与可感知性,使其不再局限于身份识别场景,而是成为连接人与设备、赋能健康管理的重要信息来源,为多领域技术升级提供了全新思路。从交互体验创新到健康监测赋能,生物特征技术正通过跨学科融合实现价值提升。本章将详细剖析指纹、人脸等生物特征在人机交互和医疗健康中的应用,展现其如何打破传统应用局限,同时探讨技术落地过程中的关键挑战与优化方案,为生物特征从识别走向跨界应用提供参考。

3.1 人机交互

3.1.1 基于指纹感知的交互技术

指纹作为最成熟的生物特征之一,传统核心应用集中于身份认证领域。然而,指纹图像包含丰富的脊线纹理、皮肤形变信息及手指身份特征,这些信息有助于手势交互的潜力。同时,指纹传感模块的小型化使其能适配智能眼镜、VR 设备、移动终端等

多种穿戴式与便携式设备,硬件条件具备。近年来研究者提出指纹在人机交互场景的多种创新应用,涵盖文本输入、3D 物体操控、智能穿戴设备控制等场景,展现了交互的灵活性与实用性。

3D 手指姿态(滚转、俯仰、偏航角度)是人机交互领域非常关注的手指属性。生物特征研究者提出了多种从指纹图像高效估计手指姿态的方法,为后续交互场景落地提供了技术基础。

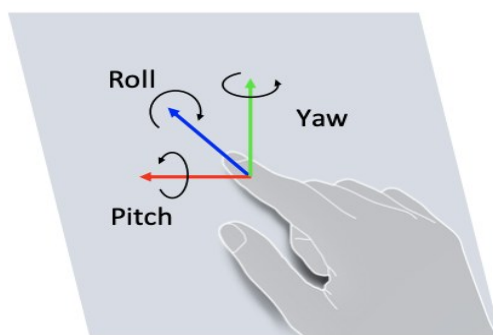


图 17 手指角度定义(Roll-滚转, Yaw-偏航, Pitch-俯仰)
Fig. 17 Finger angle definition (Roll, Yaw, Pitch)

He 等人(2022)提出多任务 CNN 架构,通过联合学习手指角度、手指类型、指纹区域分割及脊线方向四大任务,利用任务间的强相关性提升估计精度。该方法构建了包含 54285 张高分辨率指纹图像的数据集,最终实现偏航角平均绝对误差 6.6° 、俯仰角 7.1° 、滚转角 9.1° 的精准估计,显著优于基于电容触控图像的传统方法。其创新点在于首次实现了全 3D 手指角度的高精度估计,且验证了低分辨率图像(55 ppi)下的有效性,为手机等移动设备集成提供了可能。

Duan 等人(2023)进一步聚焦“相对角度估计”这一交互核心需求,提出姿态感知孪生网络。该方法通过分解指纹特征为姿态相关与姿态无关分量,利用度量学习约束特征分布,直接从两张指纹图像中估计 3D 相对旋转角度,避免了绝对角度估计中“零姿态定义不一致”的问题。实验表明,其相对偏航角 MAE 达 9.14° 、俯仰角 6.01° 、滚转角 8.41° ,在 3D 物体旋转交互任务中,完成时间与旋转误差均显著优于基于绝对角度估计的方法,更符合人机交互中相对控制的直觉逻辑。

另一类方法通过重建手指 3D 表面模型,利用 2D 指纹图像与 3D 模型的关键点匹配实现姿态估

计,具备更强的物理合理性与鲁棒性。Duan 等人(2022)提出非学习框架,首先通过注册阶段的连续指纹图像与惯性测量数据,重建手指3D表面模型;测试阶段通过指纹细节点与3D模型的投影匹配,最小化投影误差以估计3D姿态。该方法无需大规模标注数据,在小样本场景下仍表现稳定,实现滚转角平均绝对误差 10.74° 、俯仰角 8.25° 、偏航角 7.38° 的估计精度,且对指纹形变与皮肤状态变化具有较好的适应性。其核心价值在于为缺乏标注数据的场景提供了可行方案,降低了技术落地的数据集依赖。

文字输入是人机交互的核心任务之一。Liu 等人(2022)提出的PrinType指纹打字技术,通过“指纹区域/身份映射按键”的思路,解决了传统穿戴设备(虚拟现实VR、智能手表)文字输入不便的痛点。该技术将拇指佩戴的微型指纹传感器作为输入终端,识别手指不同区域(指尖、指腹、指节等)对应的按键映射,设计了全手指键盘、双手指尖键盘、单手键盘三种布局。该技术利用SIFT算法实现指纹区域精准匹配,结合统计语言解码器降低输入误差,在VR场景中实现平均 $29.56\sim 34.22$ WPM的输入速度,未校正误差率低于 0.8% 。其创新点在于首次将手指全域作为交互面,无需额外输入设备,且支持大小写字母、数字、标点的完整字符集输入,适配VR办公、移动通讯等场景。

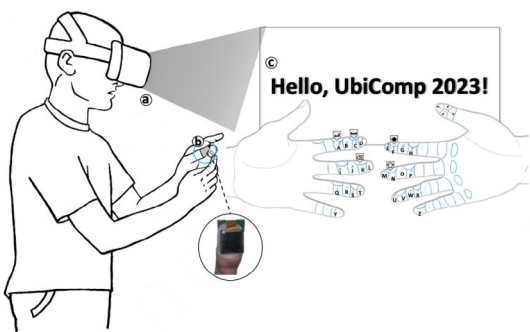


图18 PrinType微型指纹传感器布局与键盘映射示意图
Fig. 18 PrinType Miniature Fingerprint Sensor Layout and Keyboard Mapping Diagram

3D物体操控(如VR/AR中的模型调整、CAD设计)需要多自由度(DOF)控制,指纹形变特征为多维度操控提供了天然支持。Yu 等人(2023)提出Print-Shear技术,从指纹图像中提取横向、纵向及旋转形

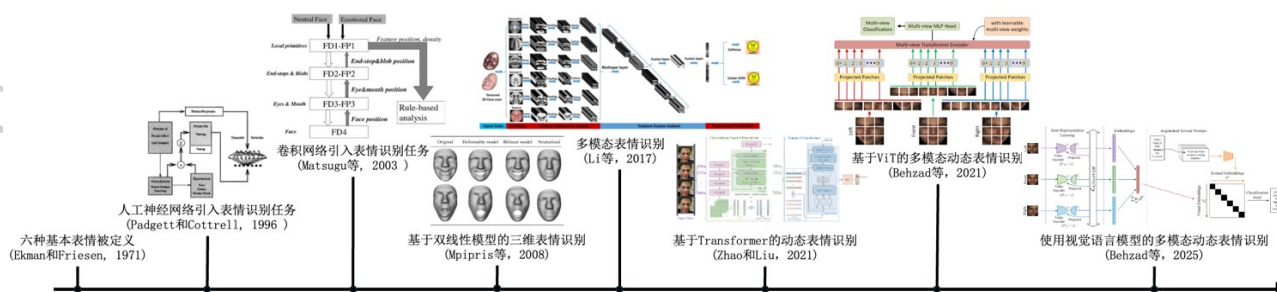
变,映射为3DOF控制指令;通过识别手指不同接触区域,可拓展至6DOF操控(旋转+平移)。该方法无需额外传感器,仅通过指纹形变分析实现交互,在3D对接任务中,相较于传统触摸输入,3DOF旋转任务完成时间缩短 14.65% ,6DOF全操控任务完成时间缩短 19.79% ,且主观负担更低。其核心优势在于利用指纹形变的连续性与精准性,实现“力-控”一体化交互,避免了传统多手势操控的复杂度与误触发问题。

智能穿戴设备(如智能眼镜)受限于体积与场景需求,需要隐蔽、高效的交互方式,指纹传感器的集成化设计为此提供了理想解决方案。Xu 等人(2025)提出FingerGlass技术,将指纹传感器无缝集成于智能眼镜镜腿,通过CNN+LSTM网络联合识别手指身份与4类9种手势(滑动、滚动、旋转、点击)。该技术将手指身份与手势组合映射为智能眼镜控制指令(如音量调节、曲目切换、文本输入),实现 96% 以上的手势识别准确率,文本输入速度达每分钟 12.72 字,响应时间仅 73ms 。其创新点在于兼顾了交互的隐蔽性与丰富性——相较于语音指令(隐私泄露风险)、触控板(输入空间有限),FingerGlass的侧置传感器设计符合人体工学,手势操作无需夸张动作,更适合公共场景使用,为智能眼镜的普及提供了关键交互支撑。

图19 人脸表情识别研究的重要节点和文献

Fig. 19 Important nodes and literature on facial expression recognition research

指纹特征在人机交互领域的创新应用,打破了指纹仅用于身份认证的传统认知,通过挖掘指纹图像中的身份信息、区域特征、形变规律及空间姿态,构建了“感知-映射-控制”的完整交互链路。这类应用的核心优势在于:一是交互的自然性,指纹传感与手指操作的天然契合,降低了用户学习成本;二是集成的便捷性,微型化指纹传感器可无缝嵌入各类设备,无需额外硬件负担;三是控制的精准性,指纹特征的唯一性与形变的连续性,保障了交互的低误差率。未来,随着柔性指纹传感技术、多模态融合算法的发展,指纹交互有望进一步拓展至更多场景,如残疾人辅助设备、精密仪器控制等,成为生物特征“跨界应用”的典型范例,推动人机交互向更高效、隐蔽、自然的方向演进。



3.1.2 人脸表情识别

人脸表情识别技术是情感计算领域的重要研究方向。随着计算机视觉的不断发展,其技术路线已从早期依赖手工设计的纹理特征,演变为深度模型驱动的高维表征,并进一步扩展到三维几何、多模态融合以及与大模型协同的最新范式。在这一过程中,表情识别在表征能力、鲁棒性与泛化性能上均取得了显著提升,逐渐形成了如图19所示由二维、三维到多模态的完整发展脉络。

在人脸表情识别的早期阶段,研究主要围绕二维静态图像展开。1996年,Padgett与Cottrell(1996)首次将人工神经网络引入表情识别任务,为深度学习方法在该方向的应用奠定了基础。随后,Matsugu等人(2003)利用卷积神经网络进行表情分类,展示了神经网络在视觉任务中的优势;Ranzato等人(2011)进一步采用深度信念网络(Hinton等,2006)学习多层表征,推动二维静态表情识别进入深度学习时期。在此基础上,研究者开始探索更加结构化和可解释的深度体系。例如,Ding等人(2017)提出FaceNet2ExpNet,通过建模FaceNet高层神经元响应的概率分布来约束FER特征空间,从而提升判别性能。

随着视觉Transformer在多类视觉任务中的成功,人脸表情识别也开始引入更灵活的注意力机制,以捕获复杂的面部区域依赖。Huang等人(2021)提出结合局部网格化注意力与Transformer的方法,实现从低层纹理到高层语义的多尺度建模。Xue等人(2021)的TransFER网络引入多头自注意力丢弃等模块,使模型能够自适应聚焦关键区域并构建关系敏感的表情特征。Li等人(2024c)提出的FER-former则在多粒度嵌入、混合自注意力以及异构领域监督的支持下,将CNN与Transformer有机结合,为复杂环境下的表情识别提供了更具泛化性的解决方案。

二维方法的局限使研究者开始关注表情随时间变化的动态特征,视频表情识别因而受到重视。早期方法(Liu等,2022)多采用LSTM聚合CNN或ViT提取的帧级特征,以捕捉跨帧时序关系。随着Transformer结构的发展,Former-DFER(Zhao和Liu,2021)在网络中分别构建空间与时间Transformer块,实现对空间结构与时间依赖的联合建模,从而显著提升动态识别能力。近期研究(Tong等,2022)进一步将自监督学习引入视频表情识别领域,利用大规模无标签视频学习可迁移的动作表征。例如,MAE-DFER(Sun等,2023)在VideoMAE框架基础上增设局部-全局交互Transformer(LGI-Former)编码器,并加入动态图重建目标,从而在时空表征能力上取得更大提升。

尽管二维静态与动态方法取得了良好进展,但它们仍然容易受到光照、遮挡与姿态变化的干扰。三维人脸数据因其稳定的几何结构,被视为解决这些问题的重要途径。早期工作如Mpipris等人(2008)的方法基于双线性模型分解三维人脸的身份与表情因素;Zhen等人(2016)借鉴解剖学模型,以肌肉形变驱动表情变化建模。随着几何深度学习的发展,Chen等人(2018)提出FLM-CNN,通过在流形卷积中引入加权操作以及采样树策略,提高了三维数据处理的效率。DrFER(Li等,2024a)则采用基于PointNet++的双分支网络,实现身份与表情特征的解耦,以增强表情特征的判别性。此外,Li等人(2024b)基于“预训练-微调”范式,在大规模通用点云与三维人脸数据上进行渐进式自监督预训练,再迁移至目标任务,显著提升了三维表情识别性能。

由于三维数据缺少纹理细节、二维图像又在鲁棒性上存在不足,多模态表情识别开始成为重要趋势,其核心目标是将二维纹理与三维几何优势互补。早期多模态方法如Li等人(2017)的框架利用VGG16-M分别提取纹理、深度、法向量与形状指数

的特征,并在通道维度融合以进行分类。随后,注意力机制被引入以突出跨模态的重要局部区域,如DA-CNN(Zhu等,2019)通过空间注意力增强模态间协作表征。为在效率与性能间取得平衡,OGF2Net(Lin等,2020)采用双分支处理纹理与几何投影,并在后期融合,从而显著降低了计算量。另一方面,Sui等人(2021,2023)的一系列工作引入基于关键点的结构先验,通过掩码机制强化局部表情区域的建模能力,FFNet与AFNet均展示了良好的融合性能。

近年来,多模态表情识别与大规模视觉模型相结合成为新的研究方向。Behzad等人(2021)首次将Vision Transformer引入该任务,通过对多视角RGB与几何图像进行特征提取,并以投票方式整合预测,提高了整体鲁棒性。随后,他们提出AffectVLM(Behzad等,2025),将CLIP(Radford等,2021)引入表情识别,通过跨模态对比学习对齐图像特征与语义空间,使模型具备更强的泛化能力。进一步地,Li等人(2025)设计结合图像与点云的双分支Transformer框架,通过跨模态适配器和提示标记实现动态融合,为三维与多模态表情识别的未来发展提供了新的思路。

3.2 医疗健康

3.2.1 基于人脸表征的生理信号测量

心率(heart rate)、心率变异性(heart rate variability)和呼吸率(respiration rate)等生理指标是衡量人体健康、情绪和疾病状态的关键信息,可以从脉搏波(Photoplethysmography, PPG)中测得。传统PPG测量依赖接触式设备,而基于人脸视频的远距离非接触式生理信号(remote photoplethysmography, rPPG)测量技术在婴儿监护、远程医疗和情感计算等领域具有重大应用价值。该技术的基本原理是远程光电容积脉搏波描记,即利用摄像头捕获面部皮肤区域因心跳引起的血流脉动而产生的微弱的颜色变化,进而恢复出相应的血容量脉冲(blood volume pulse, BVP)信号并计算生理指标。然而rPPG信号的信噪比低,且极易受到头部运动、光照变化等因素的干扰,如何通过算法优化提取准确的生理信号是该研究领域的重要挑战。

早期rPPG生理信号测量研究主要基于传统信号处理方法和手工设计的特征。一类方法采用盲源分离技术,如主成分分析(Lewandowska等,2011)和独立成分分析(Poh等,2010),此类方法试图从RGB

三通道信号中分离出BVP成分。另一类方法基于皮肤光学反射模型进行色度空间变换,代表性工作包括CHROM(de Haan和Jeanne,2013)、POS(Wang等,2017)和PBV(de Haan和van Leest,2014)等。这些方法的优势是简单便捷无需模型训练,但测量性能有限,在受控环境下表现尚可,但在运动和光照变化等复杂场景下由于缺乏相应的应对方案而准确性显著下降。

随着深度学习的发展,研究人员开发了基于神经网络的rPPG方法,学习从面部视频到生理信号的端到端映射。代表工作主要基于卷积神经网络,例如:DeepPhys(Chen和McDuff,2018)采用双分支卷积注意力网络,分别提取运动表征(使用归一化帧差)和外观表征(使用原始RGB帧),并通过注意力机制自适应地聚焦于包含强生理信号的面部区域;PhysNet(Yu等,2019)首次使用3D-CNN直接从原始面部视频提取时空特征,并引入负Pearson相关系数损失函数,实现了精确的rPPG波形恢复而非仅估计平均心率;RhythmNet(Niu等,2020)探索了先从面部视频提取生理信号时空图(STMap)再使用2D-CNN处理的范式。这些方法相比传统方法在测量性能上取得了一定进步,但CNN的局部感受野限制了时间维度上长时序依赖关系的探索。

近年来,研究者们持续探索更强大的时空建模架构以应对上述挑战。

监督学习方面,PhysFormer(Yu等,2022)引入了时间差分Transformer架构,利用全局注意力机制建模长距离时空依赖关系。PhysFormer++(Yu等,2023)进一步采用SlowFast双路设计分别处理周期性和动态性特征,并通过交叉注意力实现双路融合。为应对Transformer处理长视频序列时的二次复杂度限制,基于状态空间模型(SSM)的Mamba架构凭借其线性复杂度和长程依赖建模能力成为研究热点。RhythmMamba(Zou等,2024)通过多时间尺度Mamba模块对脉搏波的周期模式进行状态转移建模。PhysMamba(Luo等,2024)则提出时间差分Mamba块结合SlowFast双流架构。监督学习方法的弊端是依赖大规模、高质量的标注数据,即面部视频需与同步记录的生理信号(如ECG或PPG)配对,而此类数据的获取成本高昂且流程繁琐。

无监督与自监督学习方法近年在rPPG领域受到关注。Gideon和Stent(2021)首次将对比较学习

(contrastive learning)引入rPPG领域,使用频率和时间平滑性的弱先验进行训练。Contrast-Phys(Sun和Li,2022)提出了基于时空对比的无监督学习方法:利用先验知识将来自同一视频中不同时空位置的rPPG信号片段视为正样本对在特征空间中拉近,将来自不同视频的信号片段视为负样本对在特征空间中推远,从而学习rPPG表征。Contrast-Phys+(Sun和Li,2024)在此基础上扩展,增加了弱监督训练能力,能够利用部分可用或有噪音的标签数据进行训练。SiNC(Speth等,2023)则基于周期性和有限带宽的最小假设,通过惩罚生理频带范围外的功率、鼓励功率谱的稀疏性以及批次间功率谱的方差,直接学习rPPG信号。研究者还从生成模型的角度探索提升rPPG测量的可行性。PulseGAN(Song等,2021)首次将生成对抗网络引入rPPG领域,对CHROM信号进行去噪以生成真实的脉搏波形。Dual-GAN(Lu等,2021)提出双生成对抗网络架构:BVP-GAN学习从输入到真值BVP的抗噪映射,Noise-GAN学习噪声分布,两个GAN相互促进以实现BVP与噪声的特征解耦。PhysDiff(Qian等,2025)采用扩散模型回归rPPG信号,并通过动态解耦策略捕捉rPPG信号的趋势和幅度两种特征。

多模态融合是克服rPPG在弱光和运动情况下性能不足的另一重要途径,也是最近一年研究关注的焦点方向。包括多角度RGB融合、以及RGB和近红外、射频雷达等其它传感器的融合方法。UDA-rPPG(Wu等,2025)提出通过多角度的RGB视频融合以增强在极暗光条件下的rPPG测量性能。Evidential-phys(Ge等,2025)针对视频与RF融合,引入不确定性感知机制动态评估各模态可靠性并自适应加权。FusionPhys(Ying等,2025)支持视频与近红外等多种模态组合,通过自适应调制和生理交互块实现融合范式,并创新性地提出子模态分解技术将单一视频分解为多个空间子模态。

面向多样的应用需求,rPPG技术在未来研究中还有很多待解决的问题。运动鲁棒性依然是瓶颈,现有模型在应对剧烈运动或极端光照时仍有较大提升空间。公平性与偏见也是重要议题,现有的公开数据集在人口统计学上存在不均衡,深色肤色的样本缺乏,而现有rPPG模型在深肤色样本的测量性能显著降低。在测量精度上,对于心率变异性 and 血压等相关的生理指标,其精度和可靠性的研究尚不充

分。数据隐私安全是rPPG技术发展需要考虑的另一个因素,人脸视频是包含身份信息的个人隐私数据,一些场景并不允许录制和存储这类身份信息,如何从匿名化处理的视频(去除身份信息)中重建rPPG信号是引领rPPG技术安全使用的未来探索的新方向。

3.2.2 指掌静脉健康监测

COVID-19大流行深刻重塑了人机交互的方式,非接触式技术成为公共卫生安全的重要屏障。部分掌指静脉的研究重心正逐渐向生理状态感知与医疗场景赋能延伸,旨在构建一种集身份认证、健康监测与医疗辅助于一体的新型交互范式。

在生理指标监测与疾病筛查方面,研究者致力于挖掘静脉图像中蕴含的血液动力学与光谱信息,以实现非侵入式的健康评估。Somkunwar等人(2021)针对疫情防控需求,提出了一种集成温度检测和血氧水平检测功能的掌静脉身份验证系统,该系统能够在进行身份核验的同时辅助监测冠状病毒等感染症状,实现了防疫流调的自动化。针对特定生理指标的分析,Naskar等人(2024)提出了一种基于掌静脉颜色分析的非侵入性血红蛋白估计方法,为贫血的快速筛查提供了便捷手段。随着移动计算能力的提升,Islam等人(2025)推出了H2OPulse,这是首个基于智能手机的解决方案,通过分析背部和手腕静脉在不同水合状态下的可见性模式变化来进行脱水检测,极大地拓展了个人健康管理的边界。

在医疗管理与辅助诊疗领域,静脉技术被广泛应用于提升医疗操作的安全性与培训效率。针对植入式医疗器械的数据访问难题,Almukhlifi等人(2023)创新性地使用掌静脉和零水印的组合作为凭证数据,有效解决了患者失去意识无法口述密码时的紧急通信与隐私保护问题。在药物管理环节,Sawa等人(2022)将掌静脉识别算法引入患者药箱认证系统,旨在从源头上防止医院内部的药物分发与管理错误。此外,在临床技能培训与辅助成像方面,Francisco等人(2021)开发了一套具有实时模式识别功能的近红外成像系统,专门用于医务人员和医学生的插管技能发展培训;Vt等人(2021)则进一步对静脉观察器在皮肤科血管定位及美容领域的应用进行了深入分析,并提出了一系列紧凑、低成本的硬件设计方案,降低了辅助医疗设备的门槛。

4 结 语

本报告概述了生物特征识别技术近五年的研究进展、安全挑战与创新应用。在核心技术层面,各模态均实现了深度学习驱动的跨越式发展:人脸识别在检测、对齐、识别与生成四大环节形成成熟技术链条,三维感知与可控生成成为新热点;虹膜识别突破传统受控场景限制,向更多终端、开放场景演进,分割与特征表达技术日趋鲁棒;指纹识别从传统特征提取转向深度网络建模,非接触、三维采集等新模态拓展了应用边界;指掌静脉、人体、步态等模态则凭借独特优势,在特定场景中实现快速渗透,多模态融合成为提升性能的有效路径。

安全领域的攻防博弈呈现升级态势,防御技术从单一场景检测向物理-数字统一防御演进。呈现攻击检测从主动配合式转向被动检测,结合多模态大模型与因果推理提升鲁棒性;深度伪造检测聚焦时空一致性与生成伪影挖掘,合成数据训练与跨模态协同成为重要方向;隐私保护技术通过可撤销模板、加密算法与隐私计算,构建起全链路安全防护体系,但开放场景下的泛化防御仍需突破。

应用层面,生物特征已超越传统身份认证范畴,在人机交互领域实现手势识别、表情识别等创新应用,推动交互向自然、高效、安全演进;在医疗健康领域,非接触生理信号测量、静脉健康监测等技术,为远程医疗、疾病筛查提供了新手段,展现出巨大的民生价值。

未来,生物特征识别技术将朝着“高精度、高安全、泛场景、轻量化”的方向发展。大模型与具体模态的深度融合、跨域泛化能力的提升、隐私与安全的协同优化,以及在更多垂直领域的应用拓展,将成为核心研究方向。随着技术的持续迭代与产业生态的不断完善,生物特征识别将进一步重塑数字身份认证体系,为社会治理、产业升级与民生改善注入更强劲动力。

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