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The Biometric Face Recongnition System in Low Light Conditions

ABSTRACT

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INTRODUCTION

Face recognition is one of the key biometric technologies that enables identification and verification of individuals based on facial features extracted from images or video streams. Due to its non-contact operation, user convenience, and ability to perform identification at a distance, face recognition has become widely adopted in access control, surveillance, security monitoring, and smart infrastructure applications.

Despite considerable advances in machine learning and computer vision, reliable face recognition under low-light conditions remains a challenging problem. In practical applications, biometric systems frequently operate during nighttime hours or in environments with insufficient illumination, such as underground facilities, warehouses, parking areas, building entrances, and outdoor surveillance zones. Under such conditions, image quality deteriorates significantly due to reduced contrast, sensor noise, motion blur, shadows, and non-uniform lighting. These factors negatively affect both face detection and subsequent recognition accuracy, thereby reducing the overall reliability of biometric access control systems.

Machine learning and deep learning techniques, particularly convolutional neural networks (CNNs) and modern face detectors, play a crucial role in modern face recognition systems. These approaches enable efficient learning of facial features and improve recognition accuracy even under challenging conditions. However, the performance of even state-of-the-art models degrades substantially when applied to low-light imagery without appropriate preprocessing.

This research addresses the problem of face recognition in low-light conditions by developing a software module for user authentication that integrates image enhancement techniques with modern deep learning-based face detection. The proposed approach combines Contrast Limited Adaptive Histogram Equalization (CLAHE) and Retinex-based illumination correction with the YOLOv8-Face detector, achieving significant improvements in detection accuracy on the DARK FACE dataset.

An examination of the dissertation for the correctness of the use of borrowed materials using the «Antiplagiat» network resource in on-line mode on June 5, 2026 showed the correctness of the use of borrowed materials (originality is 65.41%).

GENERAL DESCRIPTION OF WORK

Objective and tasks of the research

The objective of this dissertation is to develop a software module for user authentication based on biometric face recognition in low-light conditions using machine learning techniques.

To achieve this objective, the following tasks were accomplished:

1. To provide an overview of biometric face recognition systems and their applications;
2. To analyze challenges and limitations of face recognition in low-light environments;
3. To study information security threats in biometric systems and methods of protection;
4. To investigate image characteristics and features relevant to face recognition under varying illumination conditions;
5. To explore feature extraction techniques suitable for low-light facial images;
6. To analyze machine learning and deep learning methods for face recognition and select the most effective approaches;
7. To analyze available datasets for face recognition, particularly those containing low-light images, and prepare training and testing samples;
8. To explore tools and frameworks for developing and training machine learning models;
9. To perform comparative analysis of selected methods based on performance metrics;
10. To develop a software module for face recognition in low-light conditions using the selected approach.

Object and subject of research

The object of research: machine learning and deep learning algorithms for face recognition.

The subject of research: performance metrics (accuracy, precision, recall, F1-score), robustness under low-light conditions, processing speed, and model efficiency.

Connection with priority areas of research and requests of the real sector of the economy

The topic of this thesis corresponds to modern priority areas in information security, artificial intelligence, and biometric technologies. It addresses challenges related to secure authentication systems and contributes to the development of reliable biometric solutions for real-world applications such as surveillance, mobile

security, and access control systems. The topic also corresponds to paragraph 6 «Ensuring the security of humans, society and the state (means of technical and cryptographic information protection, cryptology and cybersecurity)» of the list of priority areas of scientific, scientific-technical and innovative activities for 2021–2025.

Personal contribution of Master's degree student

The contents of this dissertation demonstrate the personal contribution of the author. The main scientific and practical results were obtained independently.

The author focused on the development of algorithms and the architecture of a software module for biometric face recognition in low-light conditions. This includes data preprocessing, feature extraction, model training, and system evaluation. Specifically:

· Conducted a comprehensive review of machine learning and deep learning methods for face recognition in low-light environments;

· Analyzed and compared publicly available datasets for low-light face recognition;

· Implemented the preprocessing pipeline combining CLAHE and Multi-Scale Retinex for image enhancement;

· Developed the enhanced face detection model based on YOLOv8-Face;

· Designed and conducted comparative experiments on the DARK FACE dataset;

· Analyzed experimental results and formulated conclusions.

The dissertation advisor supervised the research process, helped define objectives, contributed to methodology selection, participated in discussions of results, and provided scientific editing.

Practical approval and publication of Dissertation results

The main results of the dissertation were presented and discussed at scientific conferences:

XXIV International Scientific and Technical Conference «Technical means of information protection», Minsk, April 8, 2026 (in Russian).

Publication of dissertation results

Based on the research results presented in the paper, one publication was published in the conference proceedings: XXIV International Scientific and Technical Conference «Technical means of information protection», Minsk, 2026.

Structure and scope of the work

The thesis consists of an introduction, general description of the work, three main chapters, conclusion, and references. The total volume of the thesis includes multiple illustrations and tables, as well as a comprehensive list of references relevant to biometric systems, machine learning, and image processing techniques.

SUMMARY OF THE WORK

The introduction provides a brief description of the work and the reasons for conducting the research. It outlines the relevance of face recognition technology, the challenges posed by low-light conditions, and the objectives of the dissertation. The introduction also defines the object and subject of research and presents the structure of the work.

In the first chapter, machine vision technologies for face recognition are systematically reviewed. The chapter begins with an overview of face recognition systems, their applications in various domains including security, banking, healthcare, and consumer electronics. Information security threats in biometric systems are analyzed, including spoofing attacks, deepfake-based attacks, replay attacks, database breaches, and adversarial attacks. The general structure of face recognition systems is described, covering image acquisition, face detection, preprocessing, feature extraction, matching, and decision-making stages.

The chapter then provides a detailed analysis of machine learning and deep learning algorithms for face recognition. Traditional methods such as Support Vector Machines (SVM) and K-Nearest Neighbors (KNN) are compared with deep learning approaches, particularly Convolutional Neural Networks (CNNs). Activation functions (Sigmoid, Tanh, ReLU, Leaky ReLU, PReLU, Softmax) and loss functions (Cross-Entropy, MSE, Contrastive Loss, Triplet Loss, ArcFace) are examined in detail.

Special attention is given to machine learning models for face detection in low-light conditions. State-of-the-art detectors are analyzed, including RetinaFace, DSFD (Dual Shot Face Detector), PyramidBox, SSH (Single Stage Headless Face Detector), YOLOv8-Face, and REGDet. Each model is evaluated based on detection accuracy, small face detection capability, real-time performance, computational cost, and low-light robustness. The chapter concludes that REGDet achieves the highest performance on low-light data, while YOLOv8-Face provides the best trade-off between accuracy and efficiency.

In the second chapter, image processing fundamentals essential for face recognition are explored. The pattern recognition framework is described, covering image acquisition, preprocessing (noise reduction, image enhancement, normalization, ROI selection), feature extraction, and model evaluation.

A comprehensive review of datasets for face recognition in low-light conditions is presented. The following datasets are analyzed: DARK FACE (6,000+ training images, 4,000 test images, 43,000+ annotated faces captured in real nighttime scenes), UFDD (Unconstrained Face Detection Dataset with multiple environmental degradations), ExDark (7,363 images across 12 categories

under 10 low-light conditions), WIDER FACE (32,203 images, 393,703 annotated faces, the largest face detection benchmark), and CASIA NIR-VIS 2.0 (cross-spectral visible and near-infrared images for night surveillance). A comparative analysis reveals that DARK FACE is the most representative benchmark for real-world low-light face detection, while no single dataset fully addresses all challenges.

Feature extraction techniques are examined in detail. Local Binary Patterns (LBP) are described as efficient texture descriptors sensitive to noise under low-light conditions. Histograms of Oriented Gradients (HOG) are analyzed for structural edge and shape representation, though their performance degrades when gradients are attenuated by underexposure. Convolutional Neural Networks (CNNs) are presented as the most effective approach due to their ability to automatically learn hierarchical features invariant to illumination variations. The chapter also covers visualization techniques including feature maps, activation heatmaps (Grad-CAM), and t-SNE projections for embedding space analysis.

Evaluation metrics for face recognition systems are defined, including Equal Error Rate (EER), Recognition Accuracy (ACC), Precision, Recall, and F1-Score. The importance of these metrics for validating models in low-light environments is emphasized.

In the third chapter, the development of the face recognition system is presented. The comprehensive hardware and software environment is described in detail. The hardware configuration includes an NVIDIA RTX 3080 GPU with 10 GB VRAM, Intel Core i7-13700K processor, 64 GB DDR5 RAM, and 2 TB NVMe SSD. The software stack is built on Ubuntu 22.04 LTS, Python 3.11, PyTorch 2.1.2, and the Ultralytics library for YOLO implementation. OpenCV, NumPy, scikit-learn, and Pandas are used for image processing, mathematical operations, evaluation, and data management.

An experimental comparison of models is performed on the DARK FACE dataset. The results demonstrate that SSH achieves 78.2% accuracy, PyramidBox 82.4%, DSFD 86.8%, RetinaFace 88.5%, YOLOv8-Face 89.2%, and REGDet 92.8%. YOLOv8-Face is selected as the baseline due to its excellent trade-off between detection accuracy and computational efficiency, making it suitable for real-time applications.

The development of an enhanced face detection model for low-light conditions is presented. The proposed approach builds upon YOLOv8-Face as the baseline detector and introduces a preprocessing module consisting of two stages: (1) Contrast Limited Adaptive Histogram Equalization (CLAHE) for local contrast enhancement, and (2) Multi-Scale Retinex for illumination correction and reflectance extraction. The preprocessing pipeline is implemented online during

training and inference, with the enhanced images being fed directly into the YOLOv8-Face network.

The experimental results demonstrate that the proposed enhanced YOLOv8-Face model achieves superior performance on the DARK FACE dataset: Accuracy of 93.4%, Precision of 92.5%, Recall of 91.8%, and F1-score of 92.1%. Compared with the baseline YOLOv8-Face implementation, the proposed solution improves accuracy by 4.2 percentage points, precision by 4.5 percentage points, recall by 5.1 percentage points, and F1-score by 4.8 percentage points. The most notable improvement is observed in recall, indicating a substantial reduction in missed face detections under low-light conditions. The computational overhead introduced by the preprocessing stage remains acceptable for real-time applications, increasing inference time by approximately 12%.

Conclusion

The conducted research has demonstrated that the development of robust face recognition systems for low-light environments requires the combined application of advanced datasets, image enhancement techniques, and modern deep learning models. A comprehensive review of publicly available datasets confirmed that DARK FACE is the most representative benchmark for evaluating face detection algorithms under real nighttime conditions.

A thorough analysis of state-of-the-art face detection models (SSH, PyramidBox, DSFD, RetinaFace, YOLOv8-Face, and REGDet) revealed that YOLOv8-Face provides one of the best trade-offs between accuracy and computational efficiency, making it particularly suitable for practical deployment in real-time biometric systems.

The developed solution utilized YOLOv8-Face as the baseline detection architecture and introduced an additional preprocessing stage combining CLAHE and Retinex-based illumination correction. This approach improved image visibility and recovered facial details that would otherwise be lost under poor illumination conditions, without requiring modifications to the core detector architecture.

Experimental evaluation on the DARK FACE dataset demonstrated that the proposed enhanced YOLOv8-Face model outperformed all baseline methods considered in this study, achieving accuracy of 93.4%, precision of 92.5%, recall of 91.8%, and F1-score of 92.1%. The significant improvement in recall indicates that the preprocessing module enabled the detector to identify faces that were previously missed due to insufficient illumination.

The obtained results confirm that image enhancement techniques remain an effective and practical method for improving the performance of deep learning-

based face detection systems operating under insufficient illumination. The computational overhead introduced by the preprocessing stage remains acceptable for real-time biometric access control applications.

The research conducted within this dissertation demonstrates that the integration of low-light image enhancement and modern deep learning detectors can significantly improve the effectiveness of biometric face recognition systems deployed in challenging illumination environments. Such improvements are particularly relevant for security-sensitive applications where reliable identification and access control must be maintained regardless of environmental lighting conditions.

The applicant's list of publications

1-A. Al-Absi Saleh, S. A. E. Face recognition in low light conditions / S. A. E. Al-Absi Saleh // Tehnicheskie sredstva zaщity informacии : materиaly HXIV Mezhdunarodnoj nauchno-tehnicheskoj konferencии, Minsk, 8 aprelja 2026 goda / Belorusskиj gosudarstvennyj universиtet informatiki и radиojelektroniki [и dr.] ; redkol.: O. V. Bojprav [и dr.]. – Minsk, 2026. – S. 210–212. (in rus) Al-Absi Saleh, S. A. E. Face recognition in low light conditions / S. A. E. Al-Absi Saleh // Технические средства защиты информации : материалы XXIV Международной научно-технической конференции, Минск, 8 апреля 2026 года / Белорусский государственный университет информатики и радиоэлектроники [и др.] ; редкол.: О. В. Бойправ [и др.]. – Минск, 2026. – С. 210–212.