AI Driven Analysis of Severely Degraded Dental Evidence for Forensic Identification:A Structured Survey

Abstract

The integration of Artificial Intelligence (AI) into forensic odontology has heralded a new era of precision and efficiency in human identification. Convolutional Neural Networks (CNNs), Transformers, and other deep learning architectures have demonstrated remarkable performance in tasks such as tooth segmentation, numbering, and dental record matching under controlled conditions. **However, a critical gap exists when these systems face real-world forensic casework: severely degraded, incomplete, or damaged dental evidence.** This survey synthesizes current advancements and proposes a systematic framework combining forensic-specific image enhancement, partial pattern matching, and uncertainty quantification for reliable AI deployment in mass disaster and cold case investigations.

1. Introduction: AI's Current Role in Forensic Odontology

Forensic odontology remains crucial for human identification, especially when other biometrics fail due to dental structures' unique resilience. AI has begun transforming this field:

- **High-performance systems** like FoID achieve 59.62% mAP on panoramic radiographs
- **Systematic reviews** report pooled sensitivity/specificity of 0.93/0.95 for identification tasks
- **Advanced architectures** using attention mechanisms and transformers show promising results

Critical limitation: Current systems assume high-quality, complete dental records—a condition rarely met in real forensic scenarios.

2. The Critical Gap: AI Failure in Real-World Conditions

2.1 Quality Dependency

Current AI systems show dramatic performance degradation with:

- Poor-quality images (low contrast, motion blur, noise)
- Fragmented dental remains
- Incomplete dental records typical in disaster scenarios

2.2 Completeness Requirements

Existing algorithms fail when evidence is partial, requiring:

- Substantial portions of dental structures to be visible
- Near-complete dental arches for reliable matching
- Optimal imaging conditions rarely available in field investigations

3.3 Environmental Damage Challenges

No current AI system adequately addresses:

- Thermal damage from fire scenes
- Chemical degradation from decomposition
- Physical trauma from explosions or accidents

3. Technical Framework from Adjacent Fields

3.1 Image Enhancement Solutions

- **Super-Resolution CNNs**: Reconstruct high-resolution images from low-quality inputs
- **U-Net & GAN Architectures**: Effective for medical image denoising and inpainting
- **Domain-Specific Enhancement**: Techniques preserving critical anatomical features

3.2 Robust Pattern Recognition

- **Spatial Transformer Networks**: Handle occluded and partial object recognition
- **Part-Based Models**: Identify individuals from isolated evidence fragments
- **Metric Learning**: Triplet loss and contrastive learning for similarity assessment

3.3 Uncertainty Quantification

- **Bayesian Neural Networks**: Provide confidence intervals for predictions
- **Probabilistic Matching**: Framework for working with incomplete evidence
- **Confidence Scoring**: Legal-ready reliability measures for forensic testimony

4. Proposed Integrated Framework

Table 1: Multi-Stage AI Pipeline for Degraded Dental Evidence

Stage	Core Objective	Key Technologies
Quality Assessment	Diagnose degradation type/severity	CNN classifiers, IQA metrics
Image Enhancement	Restore clarity and detail	SRCNNs, U-Net, GANs

Stage	Core Objective	Key Technologies
Partial Matching	Identify from fragments	Part-based CNNs, graph networks
Uncertainty Integration	Provide confidence measures	Bayesian networks, probabilistic models

5. Implementation Challenges & Solutions

5.1 Data Scarcity

- **Challenge**: Limited real degraded dental evidence
- **Solution**: Synthetic data generation through realistic degradation simulation
- **Approach**: Transfer learning from enhanced to degraded domains

5.2 Validation Complexity

- **Challenge**: Establishing ground truth for severely degraded cases
- **Solution**: Expert consensus protocols and cross-validation
- **Metric Development**: Specialized criteria for partial matching success

5.3 Ethical and Legal Considerations

- **Admissibility Standards**: Extensive validation for court acceptance
- **Bias Prevention**: Algorithms accounting for population and damage diversity
- **Privacy Protection**: Secure handling of sensitive forensic data

6. Future Directions & Impact

Immediate Applications

- **Mass Disaster Response**: Rapid identification in compromised conditions
- **Cold Case Investigations**: Re-analysis of degraded historical evidence
- **Conflict Zone Forensics**: Identification in challenging environments

Technical Advancement

- **Quality-Adaptive Algorithms**: Systems adjusting to evidence quality
- **Multi-Modal Integration**: Combining radiographic, photographic, and 3D data
- **Explainable AI**: Transparent decision-making for legal proceedings

Long-term Vision

- **Global Deployment**: Integration with forensic databases worldwide
- **Standardized Protocols**: Established procedures for degraded evidence analysis
- **Cross-disciplinary Applications**: Technology transfer to medical imaging and archaeology

7. Conclusion

The literature clearly demonstrates that while AI has revolutionized theoretical forensic odontology, a significant gap persists in practical applications involving degraded evidence. The proposed integrated framework—combining advanced image enhancement, robust partial matching, and comprehensive uncertainty quantification—represents the necessary evolution toward forensically practical AI systems. This approach promises to transform challenging identification scenarios, providing reliable solutions where current methods fail, and ultimately enhancing justice delivery in the most demanding forensic circumstances.