

A comparative study on subspace detection techniques for hyperspectral image classification

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Abstract:

Hyperspectral imaging (HSI) captures detailed spectral information across hundreds of contiguous wavelength bands, allowing precise material identification and classification. In the past decade, HSI has emerged as a transformative tool for environmental monitoring, enabling applications such as pollution detection, vegetation assessment, and land use mapping. This abstract reviews recent advances in hyperspectral imaging techniques, emphasizing dimensionality reduction, classification algorithms, and spectral–spatial modeling.

Traditional dimensionality reduction methods like Principal Component Analysis (PCA) and Linear Discriminant Analysis (LDA) have remained foundational, though now commonly paired with band selection strategies such as minimum Redundancy–Maximum Relevance (mRMR). These techniques effectively reduce redundancy and improve classifier performance. Classification methodologies have also progressed, with Support Vector Machines (SVM) and Random Forests providing robust baselines, while deep learning techniques—such as convolutional neural networks (CNNs), 3D CNNs, and graph convolutional networks (GCNs)—now lead in state-of-the-art performance.

Spectral–spatial modeling has enhanced classification coherence by integrating neighborhood information. Techniques such as morphological profiles, Markov Random Fields, and deep models that merge spectral and spatial features have shown remarkable improvements in real-world tasks. These developments have enabled detection of subtle environmental features, from chlorophyll stress in crops to marine plastic debris and air pollution indicators.

Challenges remain, notably in managing high data dimensionality, reducing dependency on large labeled datasets, and ensuring model generalizability across sensors and regions. Cost and accessibility of hyperspectral sensors also limit broader deployment. Ongoing research addresses these issues through self-supervised learning, transfer learning, and hardware innovations, including drone-compatible sensors and satellite missions like EnMAP and CHIME.

Looking forward, the integration of AI-driven analytics with global-scale HSI data promises to expand environmental applications further. Multi-modal data fusion, real-time onboard processing, and the creation of open-source tools and benchmark datasets will likely define the next generation of hyperspectral environmental monitoring systems.

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Overview

Hyperspectral imaging (HSI) captures fine spectral signatures across hundreds of contiguous bands, enabling detailed analysis of environmental materials. This work presents a comparative study of **subspace detection and classification techniques** for hyperspectral image analysis — spanning from traditional dimensionality reduction methods like PCA and LDA to modern deep learning models such as CNNs and GCNs. The study highlights **spectral-spatial modeling**, **environmental applications**, and emerging trends in **self-supervised learning and multimodal fusion**, paving the way toward scalable, real-time environmental monitoring.

Introduction

Hyperspectral imaging (HSI) captures hundreds of contiguous spectral bands, enabling precise material identification across environmental surfaces. Over the last decade, HSI has become a crucial tool in pollution monitoring, vegetation analysis, and land use mapping. This study compares subspace detection and classification techniques for efficient HSI processing, highlighting trade-offs between accuracy, dimensionality, and computation.

Key Techniques — Evolution of Subspace and Classification Models

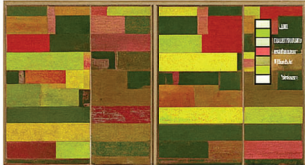
Technique Category	Representative Methods	Advantages	Limitations / Challenges
Dimensionality Reduction	PCA, LDA, mRMR	- Reduces redundancy and noise - Improves separability - Low computational cost	- May lose discriminative spectral details - Linear assumptions limit complex mapping
Classification	SVM, Random Forest	- Performs well with limited samples - Robust to overfitting - Easy interpretability	- Requires feature engineering - Struggles with spectral-spatial dependencies
Deep Learning	CNN, 3D CNN, GCN	- Learns hierarchical spectral-spatial features - High accuracy on benchmark datasets - Adaptable to nonlinear structures	- Needs large labeled datasets - High computational demand - Limited interpretability
Spectral-Spatial Fusion	Morphological Profiles, Markov Random Fields (MRF)	- Preserves spatial coherence - Reduces salt-and-pepper noise - Complements deep models	- Parameter sensitive - May oversmooth boundaries - Limited scalability for large scenes

Current Challenges

- ❖ High data dimensionality (curse of dimensionality).
- ❖ Limited labeled samples for training.
- ❖ Sensor variability affecting model generalization.
- ❖ Cost and accessibility constraints of hyperspectral sensors.

Environmental Applications

Crop and Vegetation Health Monitoring



Indian Pines (AVIRIS, NW Indiana). Indian Pines scene; crop classification and vegetation mapping using subspace-based feature extraction.

Urban and Land Use Classification



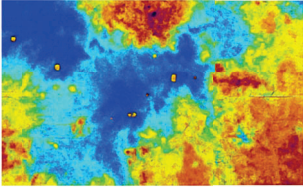
Pavia University (RDSIS Sensor, Northern Italy). Pavia University dataset: urban material classification demonstrating spectral-spatial feature fusion.

Forestry and Canopy Health Detection



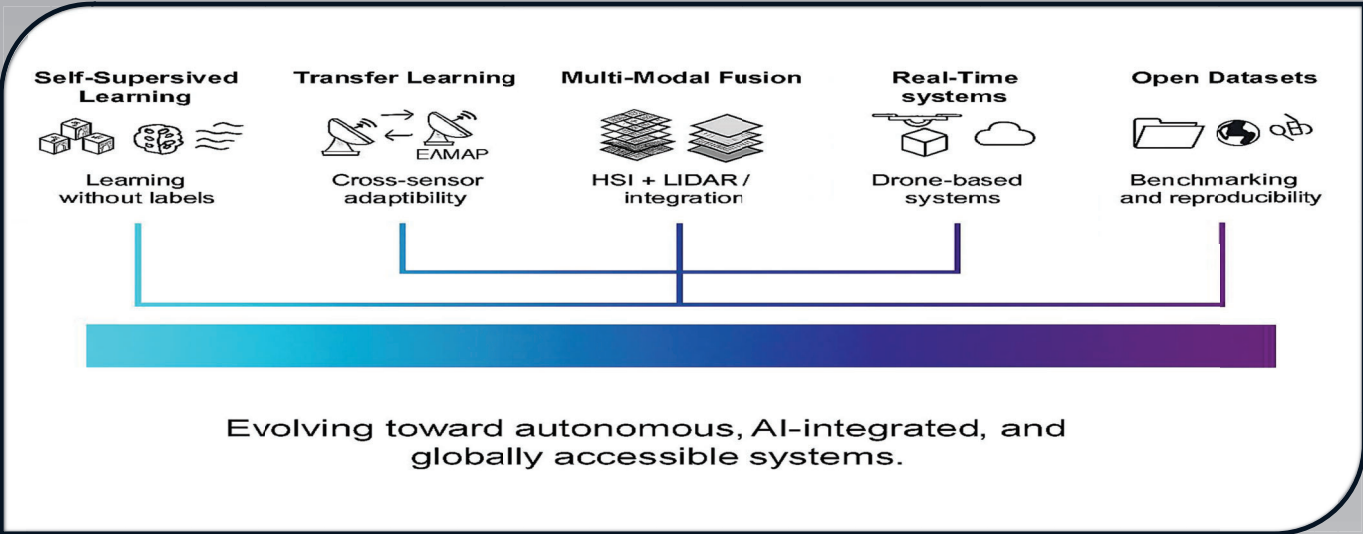
Salinas Scene (AVIRIS, Salinas Valley, California). Salinas dataset: detection of canopy stress and crop separation using subspace dimensionality reduction.

Pollution and Water Quality Analysis



Cuprite Scene (AVIRIS, Nevada). Cuprite scene: spectral unmixing and mineral detection illustrating environmental mapping capability of HSI.

Emerging Trends and Future Directions



Summary

From linear subspace projections to hybrid deep spectral-spatial frameworks, the evolution of hyperspectral classification reflects a clear trajectory toward automation, scalability, and real-time environmental intelligence. Modern HSI research emphasizes not only accuracy but also **generalization, interpretability, and sustainability**. The combination of **AI-driven analytics, sensor fusion, and open-source data ecosystems** is expected to make hyperspectral imaging a cornerstone of climate and environmental monitoring in the coming decade.