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Gamma Distribution PCA-Enhanced Feature Learning for Angle-Robust SAR Target Recognition

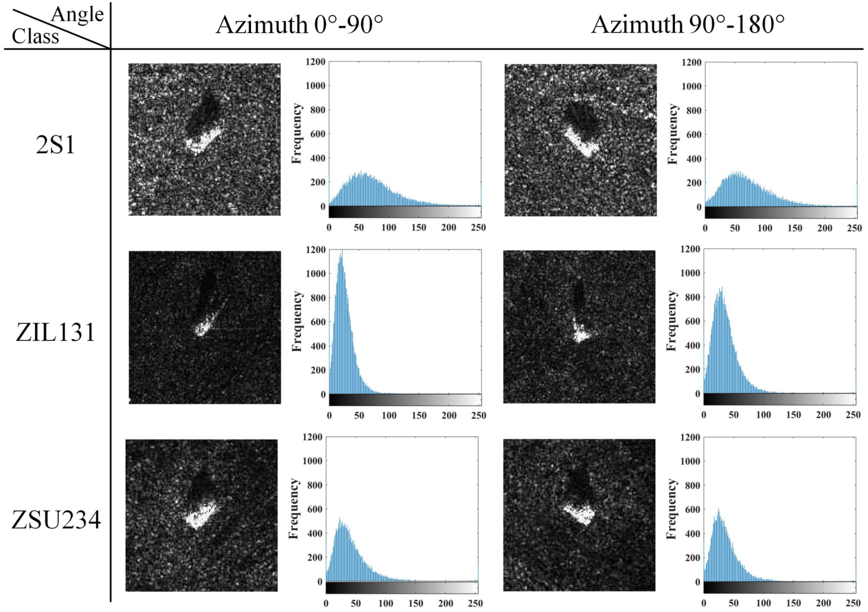
Chong Zhang, Peng Zhang*, Mengke Li*

XIDIAN UNIVERSITY 1931

SHENZHEN UNIVERSITY 1983

Reported by Chong Zhang

Introduction



Problem:

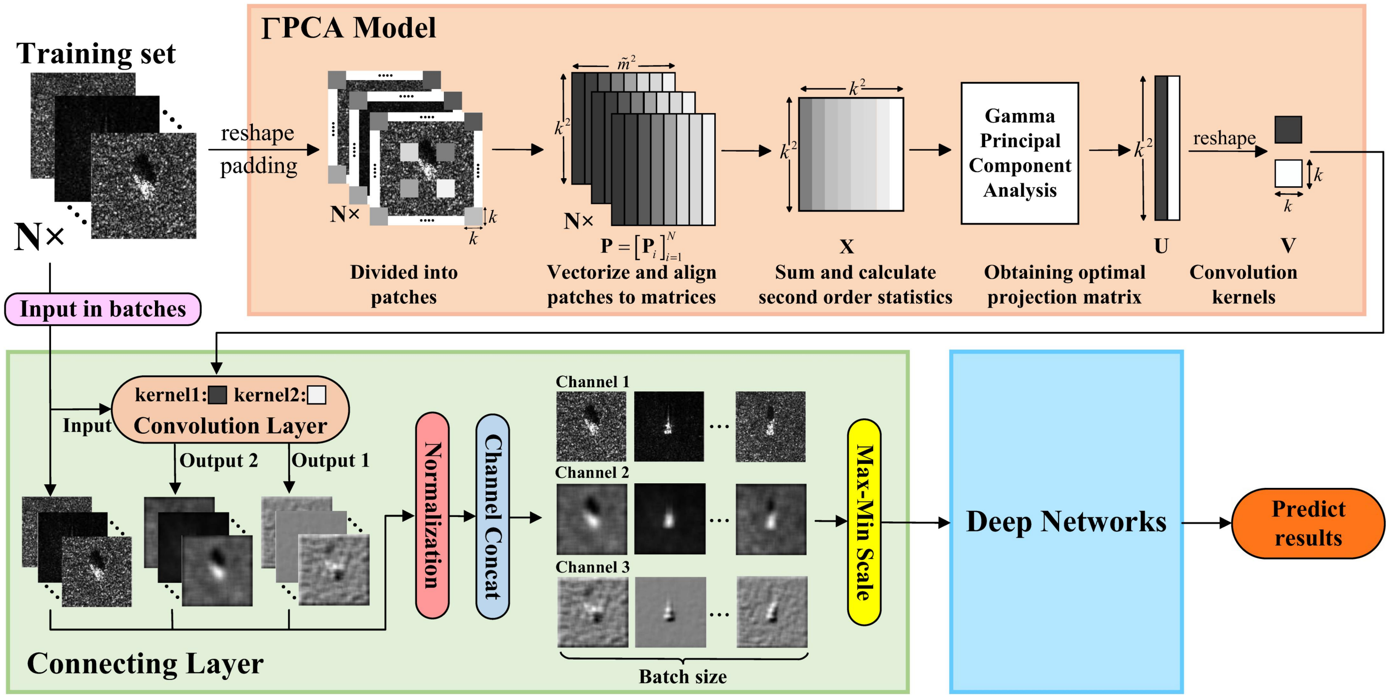
The imaging angle of synthetic aperture radar (SAR) significantly impact the scattering characteristics of targets, thereby angle-inadequate training samples leads to poor robustness of deep networks.

Motivation:

- Fully consider the unique statistical characteristics of SAR data and capture the angle-invariant feature to alleviate deep model’s sensitivity to angle variations.
- Simple, effective and readily compatible, so as to ensure its greater applicability.

Method

Model Framework



Method

Gamma Principal Component Analysis

Gamma distribution modeling

↓

Objective function of ΓPCA

↓

Optimization by MM algorithm

- Probability density function of Gamma distribution

$$f(x\,|\,\theta,\varphi)=\exp\left\{\begin{array}{l}\frac{x\theta+\log(-\theta)}{\varphi^2}+\frac{1}{\varphi^2}\log\frac{1}{\varphi^2}\\ -\log\Gamma\left(\frac{1}{\varphi^2}\right)+\left(\frac{1}{\varphi^2}-1\right)\log x\end{array}\right\}$$

- Optimization objective function

$$\max_{\substack{\boldsymbol{\mu}\in\mathbb{R}^d\\ \mathbf{U}^T\mathbf{U}=\mathbf{I}_k}}\sum_{i,j}\left\{\begin{array}{l}x_{ij}\left(\left[\mathbf{U}\mathbf{U}^T\left(\tilde{\boldsymbol{\eta}}_i(\theta)+\boldsymbol{\mu}\right)\right]_j-\mu_j\right)^{-1}\\ -\log\left(\mu_j-\left[\mathbf{U}\mathbf{U}^T\left(\tilde{\boldsymbol{\eta}}_i(\theta)+\boldsymbol{\mu}\right)\right]_j\right)\end{array}\right\}$$

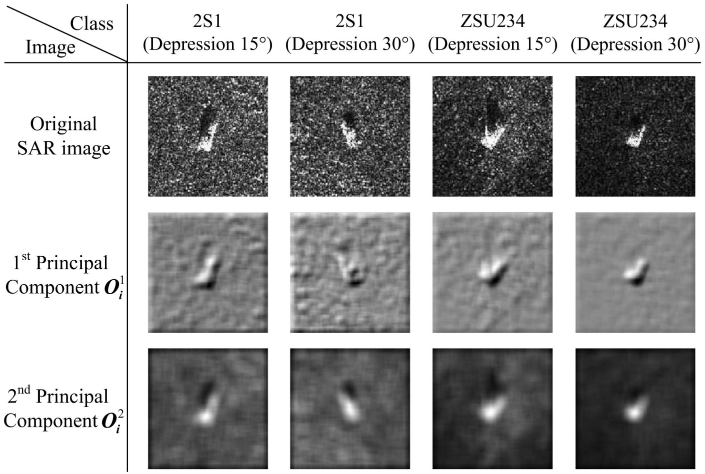
- The modification of U and μ

$$\mathbf{U}^{(t+1)}=\underset{(\mathbf{U})^T\mathbf{U}=\mathbf{I}_k}{\arg\max}\ \mathrm{tr}\left[(\mathbf{U}^{(t)})^T\mathbf{F}^{(t)}(\mathbf{H},\boldsymbol{\mu}^{(t)},\mathbf{P}^{(t)},\mathbf{Q}^{(t)})\mathbf{U}^{(t)}\right]$$

$$\boldsymbol{\mu}^{(t+1)}=(\mathbf{1}_n^T\mathbf{Q}^{(t)}\mathbf{1}_n)^{-1}\left(\mathbf{H}\mathbf{U}^{(t)}(\mathbf{U}^{(t)})^T-\mathbf{P}^{(t)}\right)^T\mathbf{Q}^{(t)}\mathbf{1}_n$$

Method

ΓPCA Feature Extraction



Our proposed ΓPCA:

- Significantly alleviates the issue of angle sensitivity for SAR data.
- No additional computational overhead for network training.
- Easy to deploy into different networks.

Experiments

Methods	A-R Test	AD-R Test	OA (%)
Resnet101	72.57±0.25	43.95±0.01	63.62±0.14
EfficientNet-B3	67.22±0.02	45.15±0.07	60.27±0.01
ViT-B/16	78.12±0.04	60.11±0.24	72.45±0.04
Swin-B	61.58±0.03	78.01±0.04	66.75±0.02
VisionLSTM-T	55.25±0.21	76.54±0.24	61.95±0.22
VisionMamba-T	62.37±0.06	66.67±0.03	63.68±0.04
MSNet-PIHA	68.08±0.03	55.75±0.06	64.20±0.03
WTConvNeXt-T	72.55±0.01	57.69±0.05	67.87±0.01
ΓPCA-Resnet (Ours)	73.79±0.02	52.96±0.05	**67.23±0.01**
ΓPCA-ViT (Ours)	78.48±0.01	70.67±0.16	**76.02±0.01**

Training set: Depression 17 Deg, Azimuth 0-90 Deg;
Testing set: Depression 15 Deg & 30 Deg, Full-Azimuth.

Methods	A-R Test	AD-R Test	OA (%)
Resnet101	75.30±0.01	48.12±0.68	66.74±0.11
EfficientNet-B3	69.24±0.09	45.69±0.07	61.83±0.07
ViT-B/16	79.92±0.04	58.56±0.12	73.19±0.01
Swin-B	70.17±0.08	65.53±0.05	68.71±0.06
VisionLSTM	55.49±0.13	74.03±1.26	61.33±0.16
VisionMamba-T	66.21±0.02	72.98±0.02	68.34±0.01
MSNet-PIHA	65.36±0.02	56.55±0.11	62.59±0.03
WTConvNeXt-T	76.46±0.07	63.29±0.51	72.32±0.16
ΓPCA-Resnet (Ours)	71.34±0.04	66.21±0.02	**69.72±0.03**
ΓPCA-ViT (Ours)	80.15±0.01	64.48±0.05	**75.22±0.01**

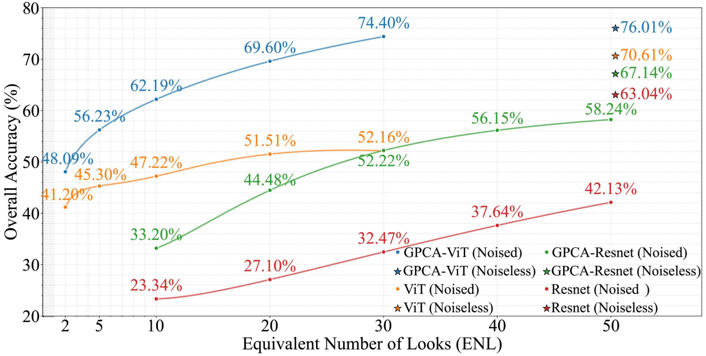
Training set: Depression 17 Deg, Azimuth 180-270 Deg;
Testing set: Depression 15 Deg & 30 Deg, Full-Azimuth.

Comparison results on MSTAR dataset

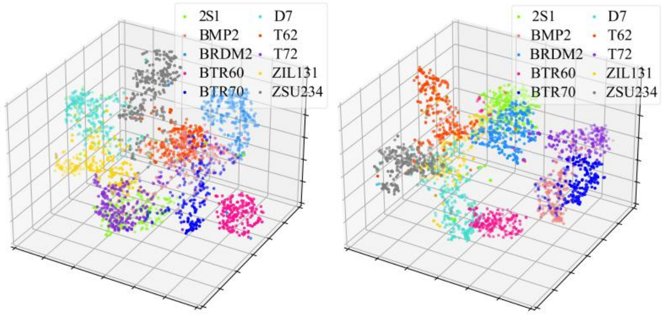
Experiments

Methods	Overall Acc. (%)
Resnet101	97.33±0.02
ΓPCA+Resnet101	**98.67±0.01**
ViT-B/16	97.05±0.03
ΓPCA+ViT-B/16	**98.12±0.02**
Swin-B	97.41±0.01
ΓPCA+Swin-B	**98.32±0.02**

- Comparison results on SAR-AIRcraft-1.0

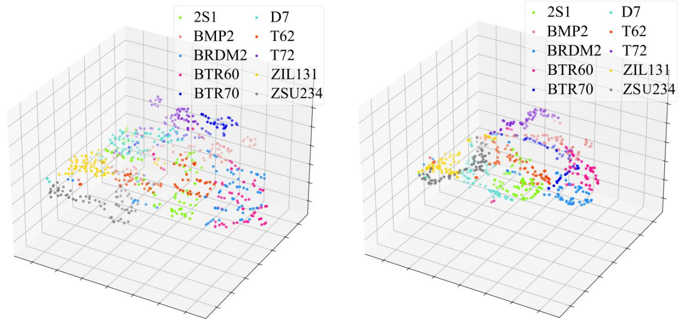


- Anti-noise performance comparison



(a) ViT-B/16 (b) ΓPCA-ViT

- ViT-B/16 vs. ΓPCA-ViT for feature extraction



(a) Standard PCA (b) ΓPCA

- Standard PCA vs. ΓPCA for feature extraction

Conclusion

Pros:

Simple yet effective and readily compatible:

- Significantly enhance the model's robustness to angle variations in the SAR ATR task;
- Can be seamlessly integrated into various deep models without introducing additional parameters.

Cons:

Appropriate hyperparameters tuning:

- For different datasets, the size of the optimal mapping matrix and the fusion approaches between principal components influence final performance.

西安电子科技大学
XIDIAN UNIVERSITY

深圳大学
SHENZHEN UNIVERSITY

Thanks

- Code: https://github.com/ChGrey/GammaPCA
- Contact: pzhang@xidian.edu.cn; csmengkeli@gmail.com

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