Hilbert Curve-Encoded Rotation-Equivariant Oriented Object Detector with Locality-Preserving Spatial Mapping

Qi Ming† , Liuqian Wang†, Juan Fang*, Xudong Zhao*, Yucheng Xu, Ziyi Teng, Yue Zhou, Xiaoxi Hu, and Xiaohan Zhang, Yufei Guo

College of Computer Science, Beijing University of Technology
School of Cyber Science and Engineering, Zhengzhou University

chaser.ming@gmail.com, jeremy.wang0126@gmail.com

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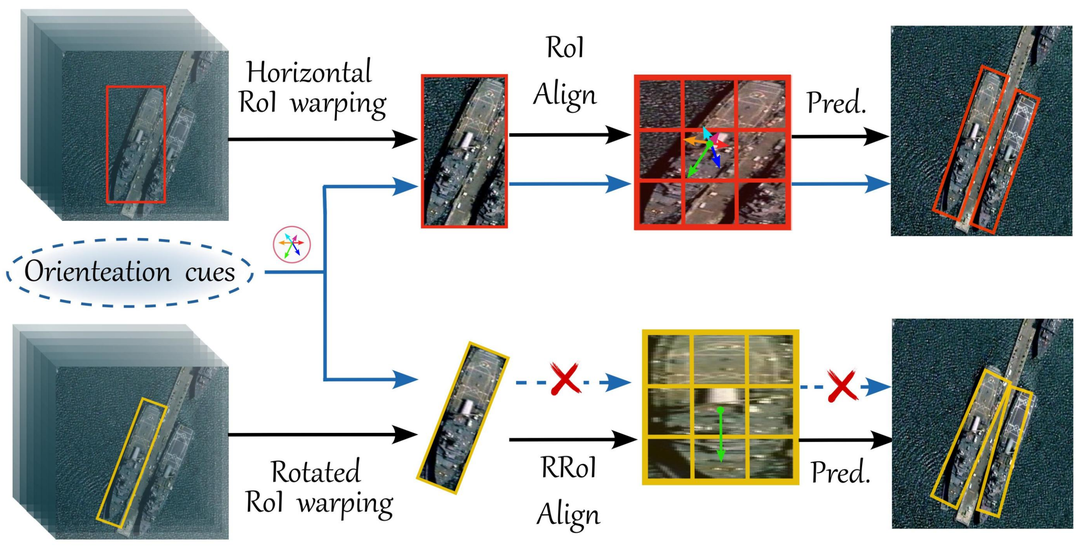
Motivation

➢ ***Orientation Prediction Bottleneck***

Two-stage AOOD frameworks use rotated RoI Align for joint classification and regression. It would *discards critical orientation information after cropping*, amplifying angle error.

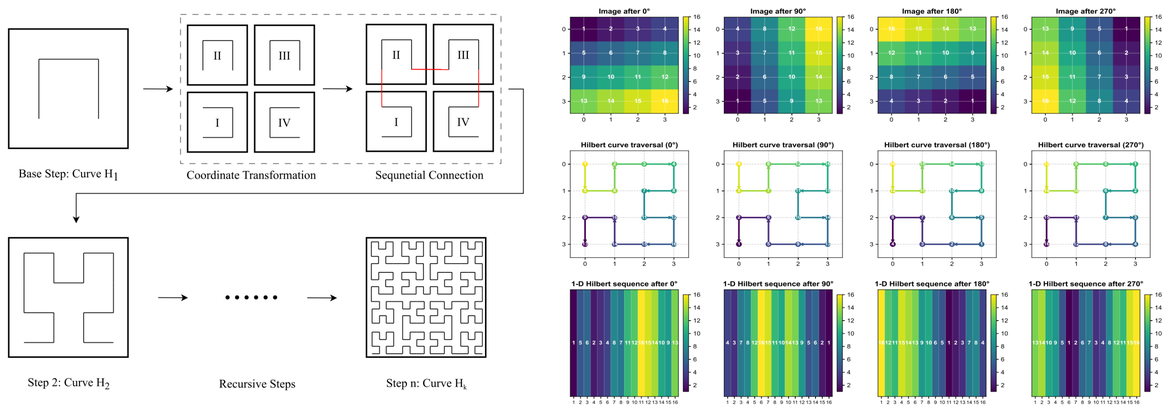
➢ ***Feature Representation Deficiencies***

Standard convolution *fails to maintain spatial coherence or leverage context*, while flattening RRoI features in stage two disrupts intra-object structure and degrades regression precision.



Preliminaries

➢ ***Definition and properties of Hilbert curves***



■ *Holder Continuity*

$$\|\mathcal{H}(x)-\mathcal{H}(y)\| \le 2\sqrt{d+3}|x-y|^{1/d}$$

■ *Scaling Property*

$$\|\mathcal{H}_k(x)-\mathcal{H}_k(y)\| = \sqrt{\alpha}\|\mathcal{H}_k(x/\alpha)-\mathcal{H}_k(y/\alpha)\|$$

■ *Inverse locality*

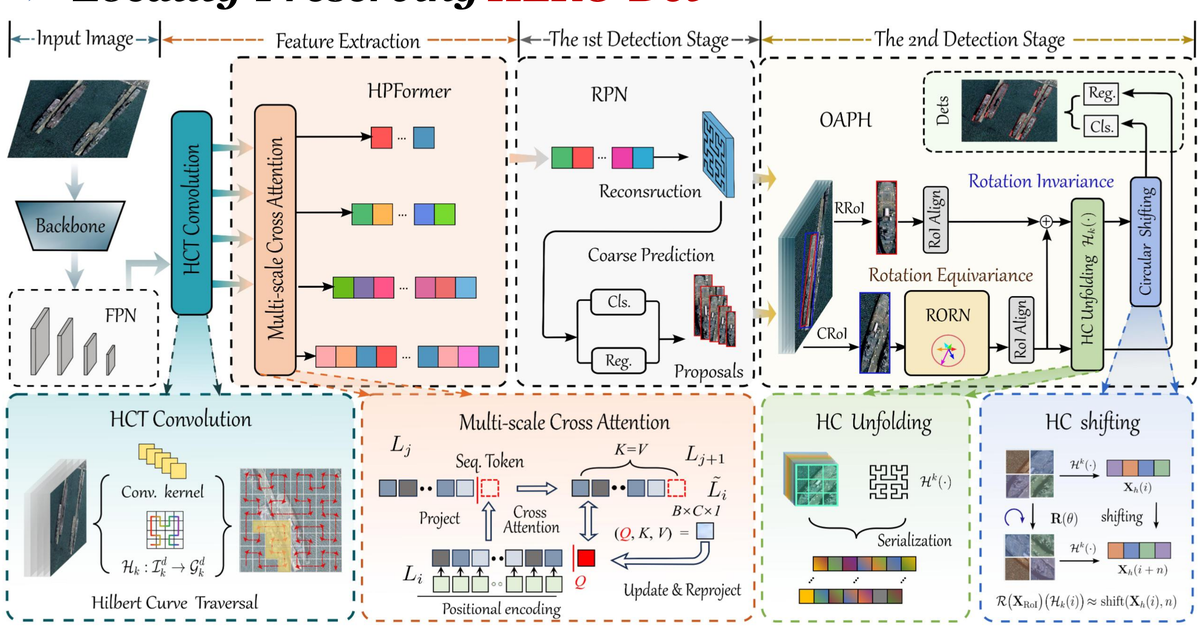
$$|\mathcal{H}^{-1}(Q_1)-\mathcal{H}^{-1}(Q_2)| \le \phi\cdot\|Q_1-Q_2\|^d$$

■ *Translation Property*

$$\|\mathcal{H}_k(x)-\mathcal{H}_k(y)\| = \|\mathcal{H}_k(x+1/\gamma)-\mathcal{H}_k(x+1/\gamma)\|$$

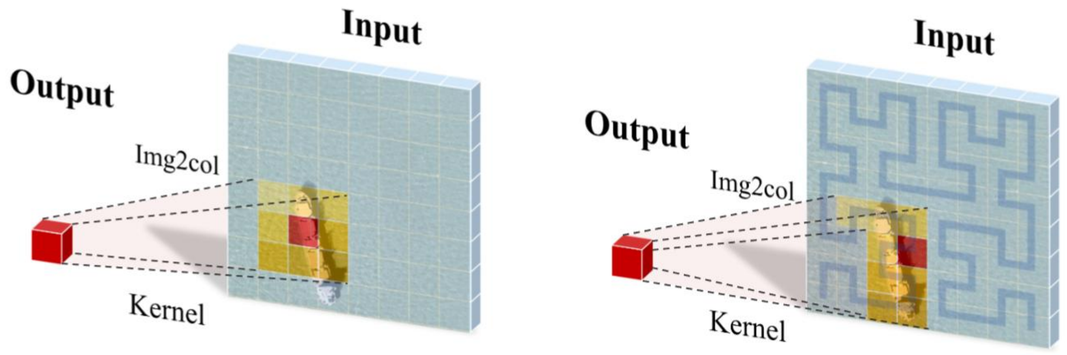
Methodology

➢ ***Locality-Preserving HERO-Det***



Based on FPN, HCTConv preserves locality, while cross-scale attention constructs HPformer. Coarse first-stage proposals are then processed via OAPH for rotation-aware prediction.

■ ***Hilbert Curve Traversal Convolution***



(a) Standard Conv. (b) Our HCTConv.

$$\mathbf{Y}(t, c_{\text{out}}) = \sum_{s\in\mathcal{N}(t)}\sum_{c=1}^{C_{\text{in}}} \mathbf{W}(s-t, c_{\text{in}}, c_{\text{out}})\cdot\mathbf{X}(\mathcal{H}_k(s), c)$$

■ ***Hilbert Pyramid Transformer***

$$\tilde{L}_i = \text{softmax}\left(\frac{\left(\tilde{L}_i W_Q\right)\left(L_{j+1}W_K\right)^\top}{\sqrt{d}}\right)\cdot\left(L_{j+1}W_V\right)$$

■ ***Orientation-Adaptive Prediction Head***

- *Residual ORN* $\mathcal{R}(\mathbf{X}_{\text{RoI}})(\mathcal{H}_k(i)) \approx \mathbf{X}_h\left((i+n\frac{N}{4}) \bmod N\right)$
- *Hilbert Curve Unfolding* $\mathbf{X}_h^{(n)}(i) = \mathbf{X}_h\left((i+n\frac{N}{4}) \bmod N\right)$
- *Hilbert Circular Shifting* $\tilde{\mathbf{X}}_{\text{RI}}(i) = \sum_{n=0}^{3}\mathbf{X}_h^{(n)}(i)$

Experiments

➢ ***Ablation Study***

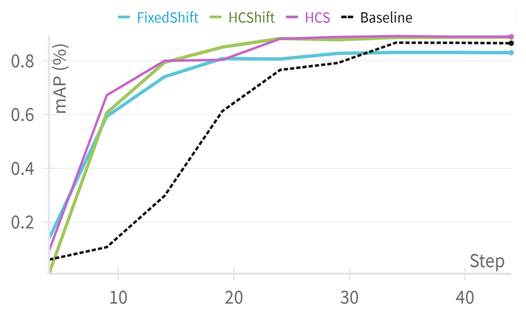
Different Variants				Metric
HCTConv	HPFormer	RORN	HCS	mAP(%)
				67.5
✓				69.1
✓	✓			70.2
		✓		68.6
		✓	✓	69.2
✓	✓	✓	✓	**70.7**

Task	3D Object detection	Image Segmentation
Model	GCIoU (Ming et al. 2023)	U-Net (Zhang, Liu, and Wang 2018)
Dataset	KITTI (Geiger et al. 2013)	Pancreatic Tumor (Ming and Xiao 2024)
Metric	Moderate AP (%)	Dice (%)
Baseline	78.5	67.6
+ HCTConv	78.9$^{(\uparrow 0.4)}$	68.7$^{(\uparrow 1.1)}$

ORN	RORN	HC Unfolding	mAP(%)
✓			67.1
✓		✓	68.1
	✓		67.5
	✓	✓	**68.6**

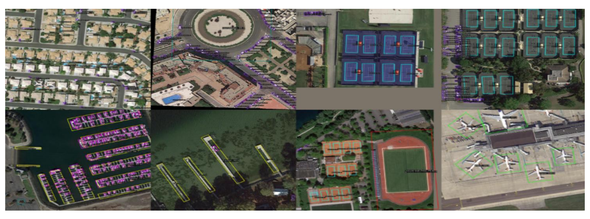
Flatten	Reconstruct	mAP(%)
——		67.5
Raster Scan	Raster Scan	67.2
Hilbert curve	Raster Scan	68.7
Hilbert curve	Hilbert curve	**69.1**

➢ ***Qualitative Results***

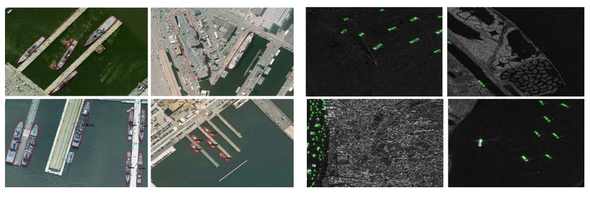


➢ ***Visualization Results***

- *Results on DOTA*



- *Results on Ship Datasets*



Conclusion

➢ Proposed HERO-Det, a novel Hilbert curve-based framework for oriented object detection with locality-preserving property.

➢ Provided an interesting idea applying space-filling curves to optimize object detection.

➢ Several known challenges remain in our HERODet, discussions are welcome !

Code **Homepage**