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Atmospheric Turbulence Mitigation in the Deep Learning Era: A Critical Revi...



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Atmospheric Turbulence Mitigation in the Deep Learning Era: A Critical Review from CNNs and GANs to Transformers, Diffusion, Mamba, and Physics-Informed Models

By [Jannah, N](#) (Jannah, Nurul) ^[1] ; [Gunawan, TS](#) (Gunawan, Teddy Surya) ^[2] ; [Kartiwi, M](#) (Kartiwi, Mira) ^[3] ; [Rahim, NA](#) (Rahim, Nadirah Abdul) ^[2] ; [Sophian, A](#) (Sophian, Ali) ^[1]

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Abstract	Anyone who has watched a distant scene shimmer above hot pavement has seen atmospheric turbulence destroy image detail. In long-range imaging, turbulence produces spatially varying blur, geometric warping, scintillation, and temporal instability. Recovering the underlying scene is therefore an ill-posed inverse problem, and learned priors must compensate for distortions that simplified optical models capture only partially. We use turbulence mitigation as the umbrella term for all countermeasures and turbulence restoration for its computational core, the estimation of a clean image from degraded observations. From a cognitive-computing perspective, mitigation is not merely image enhancement. It is an uncertainty-constrained visual inference problem in which an intelligent system must reconstruct, interpret, and act on observations relayed through a stochastic physical channel. This critical review examines how the deep learning era has reshaped turbulence mitigation, with physics as the foundation for understanding degradation and designing inductive biases. It traces the architectural progression from convolutional and adversarial networks to Transformers, denoising diffusion models, Mamba and other state-space architectures, and physics-informed frameworks. For each family, we ask a common question: How does it treat the aleatoric uncertainty intrinsic to a random optical channel and the epistemic uncertainty introduced by scarce and simulator-dominated training data? The review also analyzes datasets, simulation strategies, loss functions, and evaluation metrics, and it separates the small body of shared-protocol benchmark evidence from the far larger body of self-reported results that cannot be compared across studies. Persistent obstacles include the synthetic-to-real domain gap, the scarcity of paired real turbulence data, the mismatch between fidelity metrics and downstream task performance, and the computational cost that limits operational deployment. We close with an AI-centered agenda in which uncertainty

quantification stands alongside domain adaptation as a first-order priority.

Keywords

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Author Information

Corresponding Address: Gunawan, Teddy (corresponding author)
Surya

▼ Int Islamic Univ Malaysia IIUM, Dept Elect & Comp Engr,
Kulliyyah Engr, Jalan Gombak, Kuala Lumpur 53100, Malaysia
E-mail Addresses :

tsgunawan@iium.edu.my

Addresses :

▼ ¹ Int Islamic Univ Malaysia IIUM, Dept Mechatron Engr,
Kulliyyah Engr, Jalan Gombak, Kuala Lumpur 53100, Malaysia

▼ ² Int Islamic Univ Malaysia IIUM, Dept Elect & Comp Engr,
Kulliyyah Engr, Jalan Gombak, Kuala Lumpur 53100, Malaysia

▼ ³ Int Islamic Univ Malaysia IIUM, Dept Informat Syst,
Kulliyyah Informat & Commun Technol, Jalan Gombak, Kuala
Lumpur 53100, Malaysia

E-mail Addresses :

jannah.nurul@live.iium.edu.my; tsgunawan@iium.edu.my;
mira@iium.edu.my; nadirahabdulrahim@iium.edu.my;
ali_sophian@iium.edu.my

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No new data were created or analyzed in this study. Data sharing is not applicable to this article.

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The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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