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고현우 [1,2], 조수연 [1,2], 김상준 [1,3], 서홍석 [2], 이승아 [4], 윤선규 [5], 심재원 [2], 김진영 [6], 박민철 [1,2,3]*
*[1] 한국과학기술연구원, [2] 고려대학교, [3] 연세대학교,
[4] 서울대학교, [5] 한국광기술원, [6] 광운대학교
ckevin4747@korea.ac.kr, sooyun1324@ korea.ac.kr, kimsangjun@yonsei.ac.kr,
phseo@korea.ac.kr, seungahlee@snu.ac.kr, skyo2n@kopti.re.kr, jwshim19@korea.ac.kr,
jinyoung@kw.ac.kr, *minchul@kist.re.kr

Robust Visibility Enhancement for Public Safety Using Photodetector and AI-based Refinement

Hyun Woo Ko[1,2] Suyeon Jo[1,2] Sang-Jun Kim[1,3] Paul Hongsuck Seo[2] Seung Ah Lee[4]
Seon Kyu Yoon[5] Jae Won Shim[2] Jin Young Kim[6] Min-Chul Park[1,2,3]*
*[1]Korea Institute of Science and Technology [2]Korea University [3]Yonsei University
[4]Seoul National University [5]Korea Photonics Technology Institute [6]KwangWoon University

요 약

This study presents a hybrid imaging system for visibility enhancement in disaster environments where fog or smoke degrades perception. The system integrates near-infrared photodetector sensing with a neural refinement module to acquire physically grounded signals and improve structural clarity. Experimental results under foggy conditions show increased contrast, entropy, and fidelity compared to conventional deep learning methods. These findings demonstrate the advantage of sensor-integrated imaging pipelines for robust and interpretable perception in degraded visual environments.

Ⅰ. Introduction

In public safety and disaster response scenarios, visual perception plays a critical role in enabling situational awareness. However, environments obscured by fog, smoke, or airborne particles severely degrade visibility, making it difficult for conventional imaging systems to acquire structurally meaningful information. While recent advances in deep learning-based image restoration have shown promising results under moderate degradation, such methods fundamentally rely on the assumption that sufficient visual cues remain in the degraded input. In real-world scenarios involving dense scattering, this assumption often fails—critical features are lost during capture, and post-processing operates on insufficient or misleading data. As a result, these methods may generate plausible-looking outputs that lack physical accuracy, potentially leading to erroneous decisions in mission-critical operations [1].

To address these limitations, we propose a sensing-first hybrid imaging framework that emphasizes physically reliable signal acquisition prior to enhancement. The system integrates a near-infrared (NIR) organic photodetector (OPD) capable of capturing robust structural information through scattering media, followed by a learning-based refinement module that enhances perceptual clarity without generating synthetic content. This approach supports interpretable and low-power visibility enhancement, making it well-suited for deployment in safety-critical environments.

Ⅱ. System Overview

The proposed system enhances visual perception in foggy environments by combining near-infrared (NIR) sensing with neural refinement. As shown in Figure 1, the hardware consists of an 850 nm light source, a pinhole lens, and a single-pixel organic photodetector (OPD) mounted on a motorized XY stage. The OPD, highly responsive in the NIR range, sequentially scans reflected signals to reconstruct structural information. This imaging configuration is based on previous work using OPD-based sensing under fog [2], and has been further extended to low-power scanning [3] and

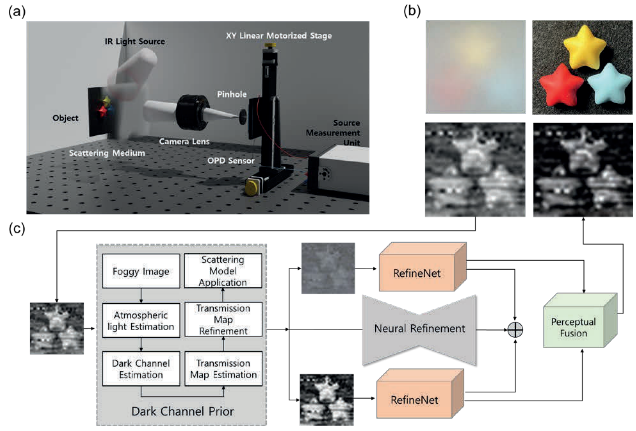

Figure 1. Architecture of the proposed visibility enhancement system: (a) NIR OPD scanning setup, (b) foggy input and refined result, (c) two-stage refinement pipeline.

integral imaging applications [4]. Fog was simulated using vaporized dry ice in a sealed chamber, and scattering effects were evaluated using the dark channel prior (DCP), which measures visibility degradation by comparing contrast under clear and foggy scenes.

Image enhancement was performed using RefineDNet [5], a two-stage dehazing model. The first stage estimates transmission and ambient light using a physics-based prior, followed by refinement with a convolutional neural network. Although trained on RGB images, the model generalized well to NIR input due to the preserved structural features captured by the OPD. These results indicate that physically grounded sensing enables reliable enhancement, even when applied outside the original spectral domain of the model.

Ⅲ. Discussion and Conclusion

The proposed system was evaluated under both simulated fog conditions and real-world scenarios. Raw images acquired by the NIR-OPD scanner preserved structural features but exhibited low contrast and residual haze. After enhancement, spatial cues became more distinct, with improved brightness and depth perception. Compared to sensing-only or refinement-only methods, the full pipeline yielded more stable results with fewer artifacts. Quantitative evaluation using PSNR, DCP intensity, and entropy supported this improvement. While foggy visible inputs showed low PSNR (6.33 dB) and high DCP (178.11), the proposed method achieved a lower DCP (28.90) and an entropy value (5.0894) close to that of the clear reference (5.2743). Field tests—including a military smoke exercise and a fire-affected outdoor scene—further confirmed practical applicability, with enhanced visibility of key objects such as tents and human figures. The system operated in real time and contributed to a CES 2025 [6].

These results underscore the value of physically grounded sensing in visibility enhancement. Unlike conventional approaches that depend solely on deep learning, the proposed framework acquires reliable input from the outset, enabling interpretable and accurate refinement. This sensing-first strategy represents a shift from restoring degraded images to proactively capturing resilient signals, offering a robust and scalable foundation for use in safety-critical environments such as disaster response, field robotics, and public security.

Figure 2. Real-world refinement results: (a) military smoke, (b) outdoor fire scene (source: JTBC).

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