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Integrating the cat's eye effect and deep learning for low-altitude target detection

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Key words: Low-altitude detection; Optical path detection; Cat's eye effect; SKNet21; Local pyramid attention; Average precision

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Motivation

1. Focusing on conventional systems' suboptimal detection accuracy in complex low-altitude environments—due to low, slow, and small (LSS) unmanned aerial vehicles (UAVs)' low altitude and high susceptibility to background, terrain, and ground object interference—this study aims to address such deficiencies.

2. Targeting traditional detection challenges from LSS UAVs' intrinsic traits (low speed/hovering, small RCS, and weak signals), the research seeks to surmount conventional limitations in detection range and discovery probability.

3. In response to the imperative demand for reliable LSS UAV detection in complex scenarios, we propose an active low-altitude target method and construct an integrated multi-module system for efficient small-target detection.

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Main idea

1. Analyzing the echo characteristics of the “cat’s eye effect” in drone micro-lenses can therefore significantly enhance the detection system’s ability to identify UAVs.

2. An omnidirectional scanning system with a shared optical path for laser and visible light is proposed. By combining micro-electro-mechanical system (MEMS) mirrors with precision servo mechanisms, the proposed system enables high-precision, omnidirectional detection.

3. By capturing both echo signals and visible light images of “cat’s eye targets” at varying distances, this approach combines convolutional neural network (CNN) models with attention mechanisms to enhance the resolution of both image types.

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Method

1. We design a method comprising a laser transmission module, an echo reception module, and optical path scanning and image acquisition processing modules to achieve co-optical-path panoramic image acquisition and diffraction echo reception, followed by echo image analysis and processing.

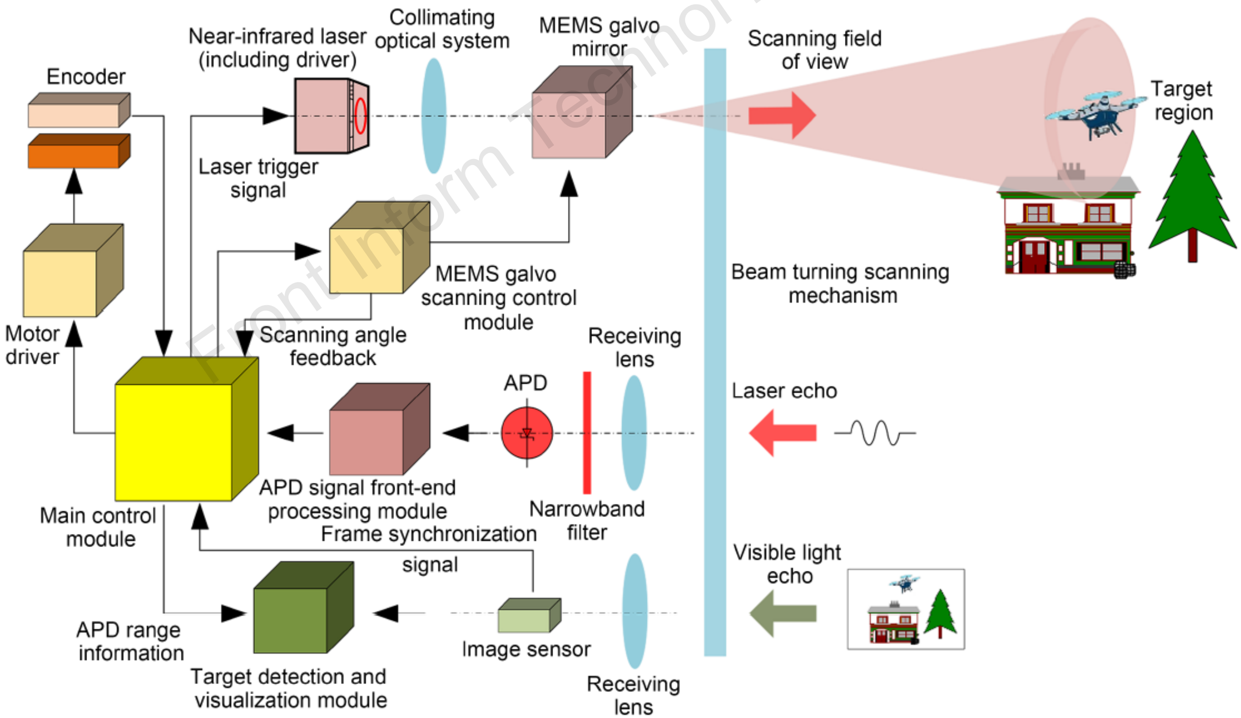

Fig. 1 Schematic diagram of the system

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Method (Cont'd)

2. To realize the amplification, acquisition, and analysis of echo signals, the front-end optical path of the detection and receiving unit is composed of a converging optical system, an avalanche photodiode (APD) unit detector, an amplification circuit, a power supply circuit, an automatic gain control (AGC) circuit, and a high-speed data acquisition and processing board.

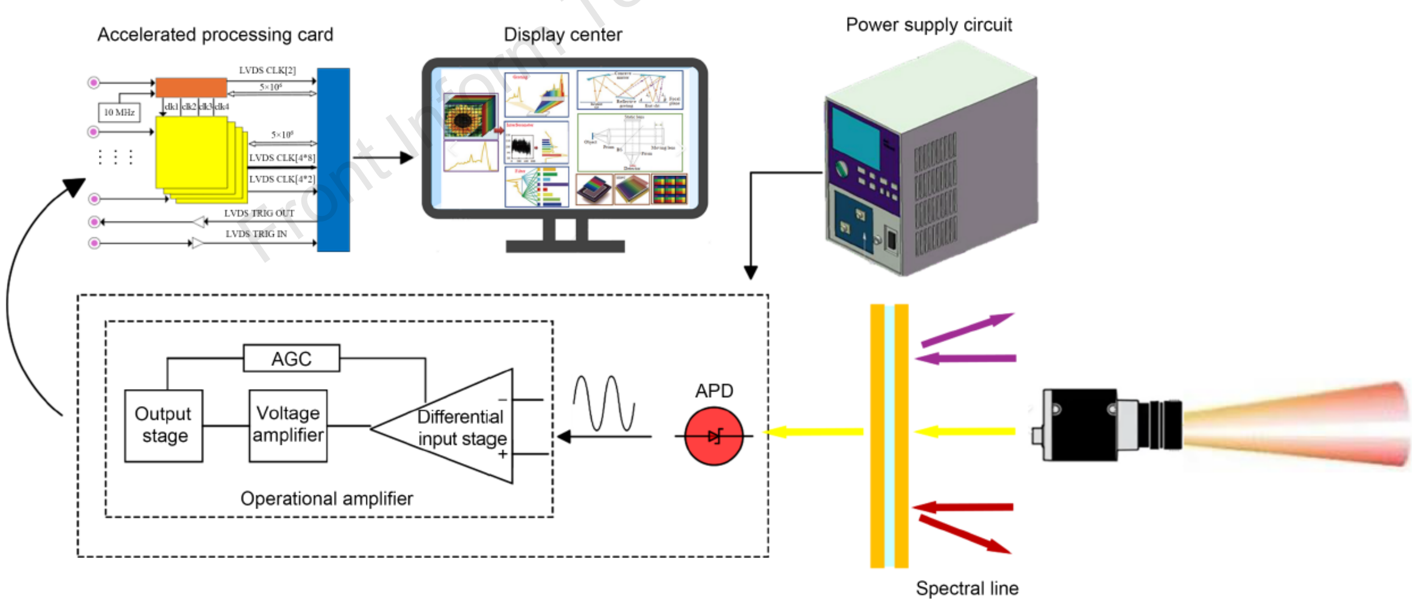

Fig. 2 Block diagram of the detection receiving end

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Method (Cont'd)

3. To address the limitations in distance and range of traditional detection systems, an opto-mechanical structure combining MEMS scanning and mechanical scanning is proposed. This structure enables forward correction of rotated images during synchronous scanning, ensuring a positive mapping relationship between the real object space and its imaging space, and reducing the difficulty of target recognition.

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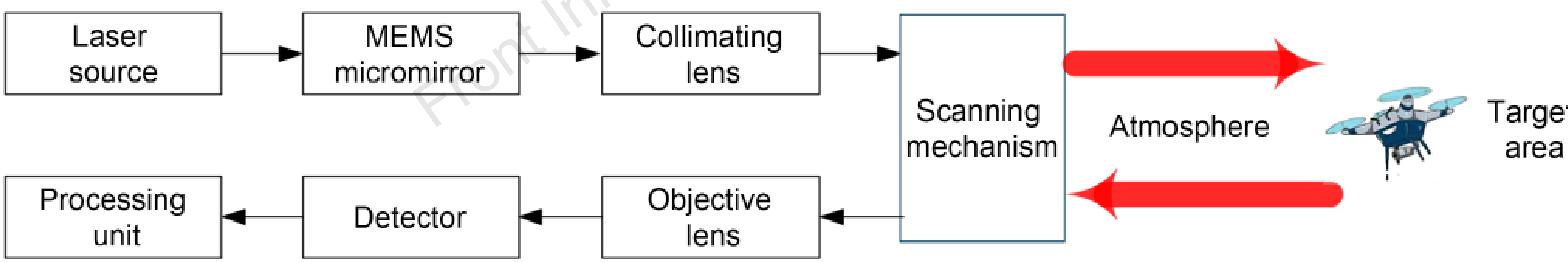

Fig. 3 Simplified diagram of the laser panoramic scanning system

Method (Cont'd)

4. By drawing on an improved residual network SKNet, the receptive field size is adaptively adjusted, and the information captured by the receptive fields effective for classification is selected.

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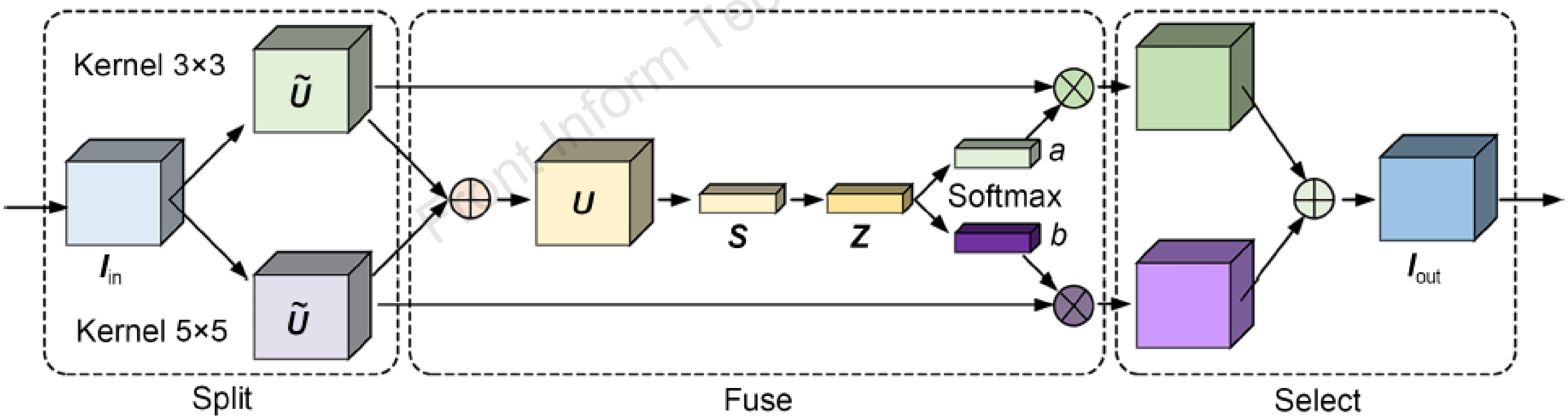

Fig. 8 Schematic diagram of SKNet

Method (Cont’d)

5. A local pyramid attention (LPA) structure is adopted to enhance relevant features, suppress irrelevant features, and complete the modeling of dependencies between long-distance pixels in different channels.

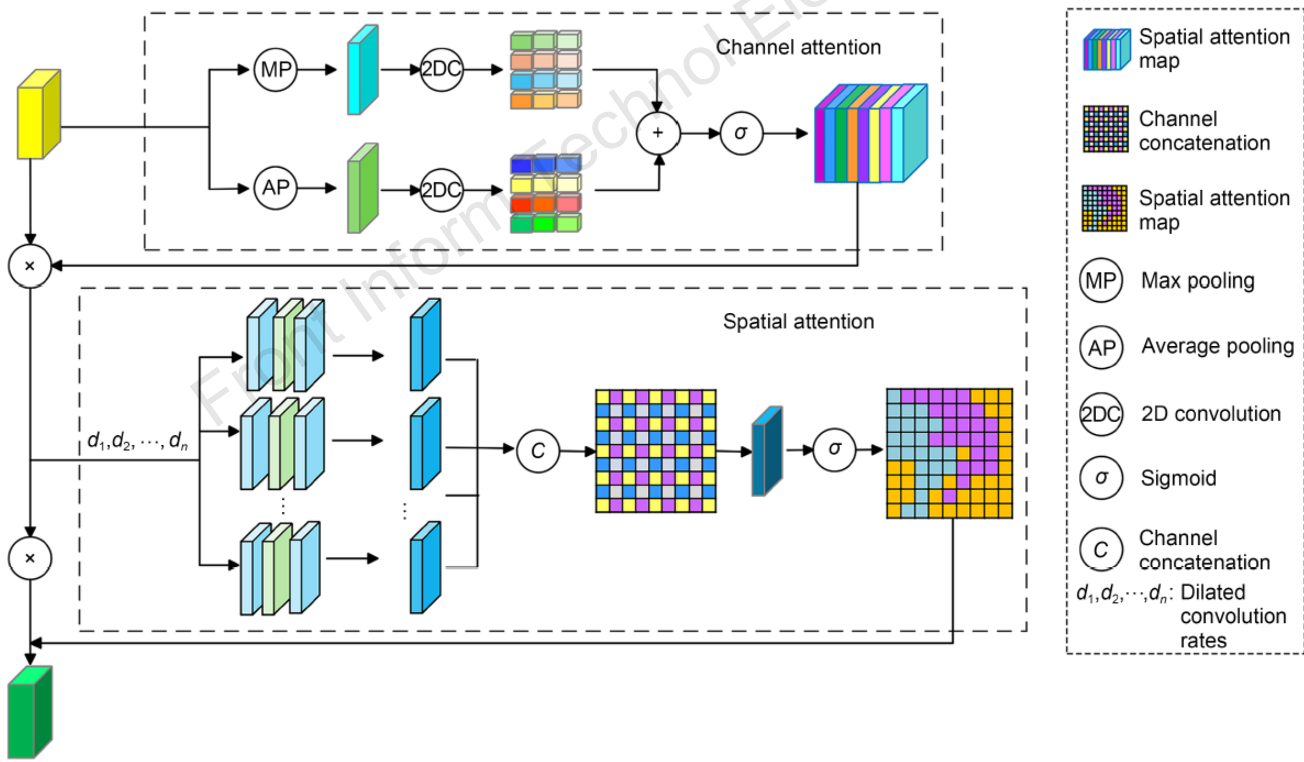

Fig. 10 Schematic diagram of the LPA module

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Major results

Simulation analysis

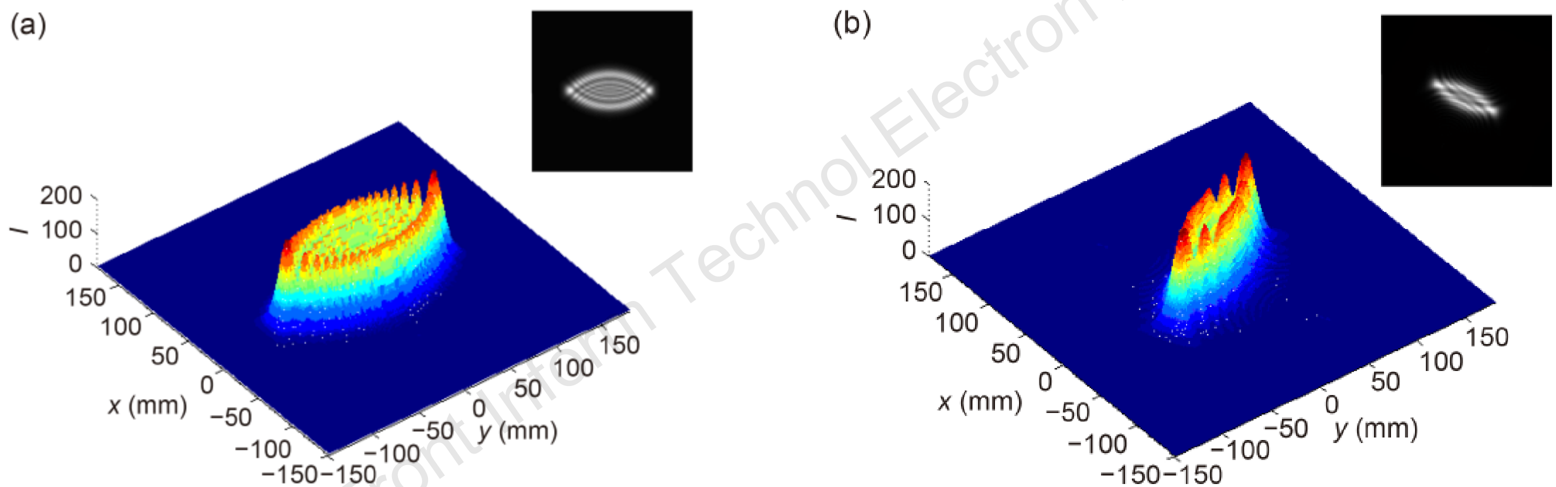

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Fig. 13 3D intensity distribution and 2D spot pattern of the outgoing beam of the ideal "cat's eye target" under the condition of laser oblique incidence: (a) θ=30° ; (b) θ=60° . I is the gray value

Major results (Cont'd)

Analysis of physical echoes

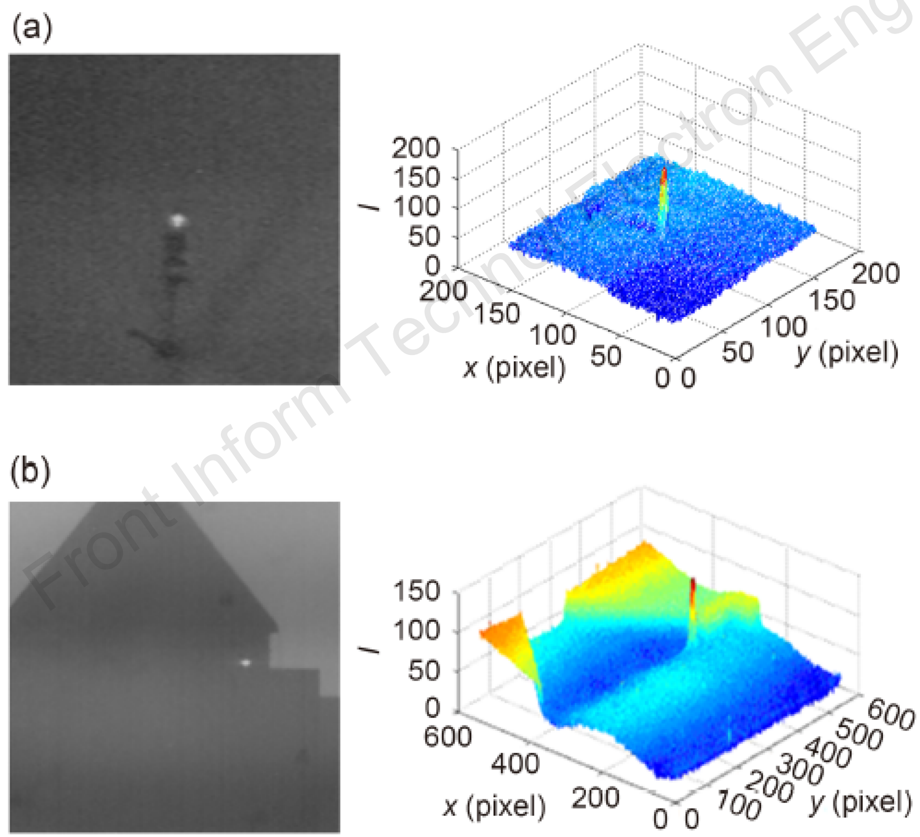

Fig. 14 Echo patterns of "cat's eye targets" at different distances: (a) 50 m; (b) 2500 m. *I* is the gray value

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Major results (Cont'd)

Comparison of different algorithms' processing

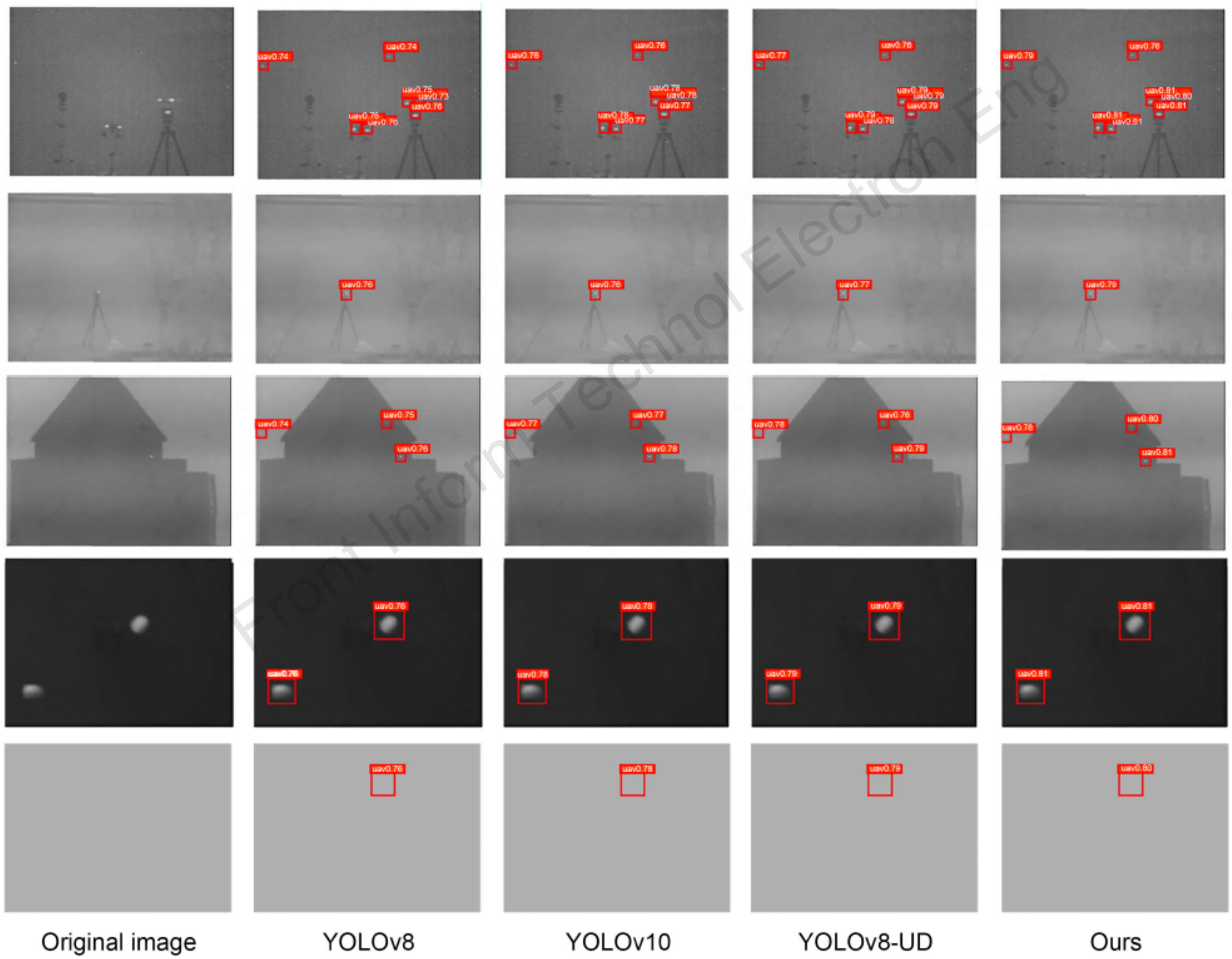

Fig. 15 Different algorithms' processing of the comparison image

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Conclusions

1. An active detection system based on the “cat’s eye effect” is proposed. Scanning is realized via NIR laser emission using MEMS mirrors and servo mechanisms, and APD receives echo signals and distance information for small target detection.

2. The recognition algorithm integrates the LPA module, FPN, and SKNet21, and combines echo intensity and flight time collected by APD to effectively eliminate false alarms and reduce false alarm rate.

3. The target detection method is verified to be feasible, with performance indicators: mean average precision of 0.809 at an intersection over union (IoU) of 0.50, a mean average precision of 0.324 at an IoU of 0.50–0.95, and GFLOPs of 49.8, which can solve current limitations in LSS target detection.

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Bin ZHOU is an associate professor and vice dean of the School of Electronics and Electrical Engineering at Zhengzhou University of Science and Technology. He earned a Ph.D. in optical engineering from the Army Engineering University. His research focuses on electro-optical countermeasures and electro-optical information processing. He has presided over two provincial-level scientific and technological research projects, participated in more than 10 others, and published over 20 papers indexed by SCI/EI. He holds three authorized national/defense invention patents.

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