

Beyond Limits: Polarization Unlocks Scene-level 3D Imaging

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The rapid development of artificial intelligence and autonomous systems makes it crucial to achieve high-precision, highly robust, and accurate real-time 3D perception, understanding, and intelligent decision-making in complex scenes. Methods such as stereo vision, structured light, or lidar, often suffer from reduced accuracy or limited applicability under challenging conditions like weak textures, strong reflections, mixed materials, and intense ambient light interference. Particularly, the trade-off between long-range detection and high precision remains unresolved. In contrast, 3D imaging technology based on polarization characteristics of light establishes a bridge from “polarization to contours”, demonstrating unique advantages in 3D perception. The major challenges lies in: □distortion in reconstruction (caused by the periodicity of trigonometric functions); □loss of absolute depth information (due to the representation of normal fields); □Inapplicability to natural scenes (resulting from multiple discontinuous and complex targets).

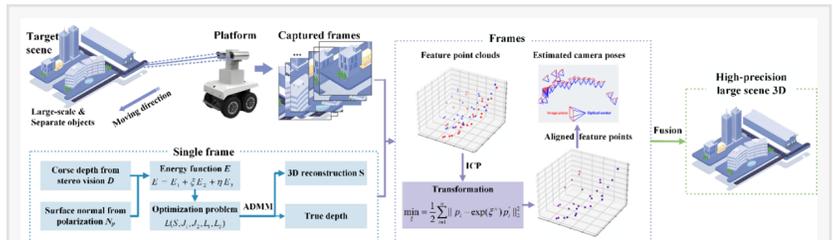


Fig.1 Overall framework for scene-level passive polarization 3D imaging

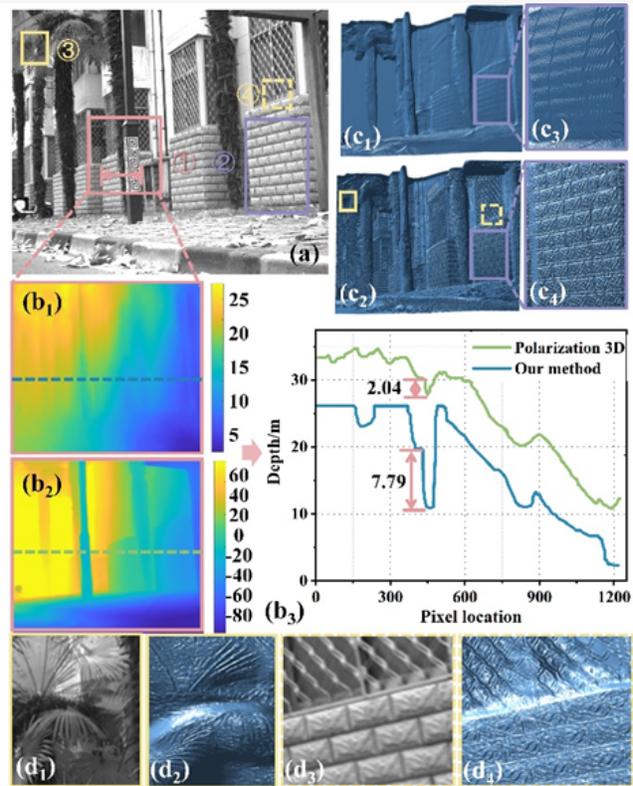


Fig.2 Real-world scene reconstruction results

To address the aforementioned challenges, polarization 3D imaging has primarily progressed

along two directions: introducing external resources as prior information to guide polarization analysis and eliminate ambiguities, and applying multi-source information fusion to transform relative depth into absolute depth. While these methods have achieved significant progress in reconstructing simple objects and continuous surfaces, they often lack specialized mechanisms to handle spatial discontinuities in large natural scenes. This limitation can lead to depth abruption or even reconstruction failures Therefore,

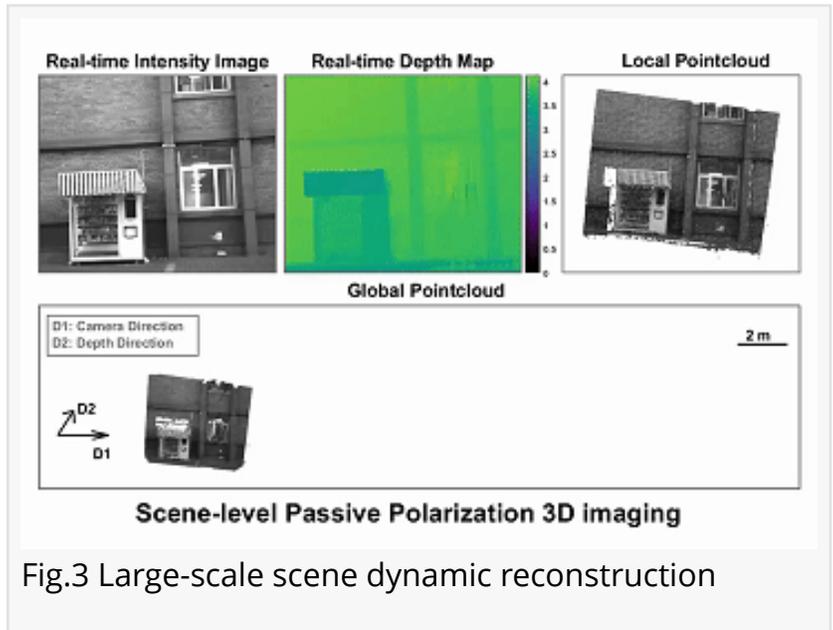


Fig.3 Large-scale scene dynamic reconstruction

passive and high-precision 3D imaging of discontinuous and complex natural scenes is a critical focus for the future advancement of 3D imaging technologies.

The authors of this article have proposed and implemented a scene-level passive high-precision polarization 3D imaging method. An integrated polarization stereo imaging system was designed and developed an iterative optimization algorithm based on polarization characteristics and stereo vision constraints. This approach systematically resolves key challenges of polarization 3D imaging including discontinuous targets, absolute depth interpretation and dynamic reconstruction. Finally, scene-level high-precision 3D imaging is realized.

In detail, the research models the 3D reconstruction of discontinuous scenes as a mathematical optimization problem. By integrating stereo vision and polarization, pixel-level surface normal derived from polarization and absolute scale information provided by stereo vision are incorporated as mutual constraints under a unified optimization framework. Through iterating for solution, it well addresses the challenge of discontinuous targets reconstruction and achieves accurate true depth. For dynamic reconstruction, the authors design a scale normalization strategy to globally align and spatially calibrate multi-view measurement data, effectively eliminating scale drift issues. Finally, high-quality 3D reconstruction of natural scenes is accomplished through multi-frame point cloud fusion. Experiments demonstrate that this method can achieve scene-level and high-precision 3D reconstruction at video rates, offering a novel and effective solution for scene-level 3D imaging.

Notably, this research achieves passive scene-level polarized 3D imaging, with no need for any active information. The pixel-level information interpretation ensures that 3D imaging accuracy depends solely on the camera's resolution. It then advantages in non-contact operation, no scanning, no radiation, and high precision. Furthermore, the core physical mechanism of this technology is universal. Its principle of inferring surface normal from polarization can, in theory,

be extended to various natural scenes. In future, by integrating multispectral polarization imaging and deep learning-based prior modeling, interference from strong stray light and other disturbances can be further suppressed. This holds promising potential for important applications such as autonomous driving, remote sensing monitoring, and cultural heritage preservation. Moreover, the mathematical solution for the high-precision 3D inversion problem based on polarization cues in discontinuous natural scenes also contributes to a deeper understanding of light-matter interaction and multi-dimensional information fusion. This advancement promotes the interdisciplinary integration and innovative development of polarization optics and computer vision.

Keywords: 3D imaging, polarization, natural scenes

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The Advanced Imaging and Extreme Detection (AI-XD) Team is led by Professor Fei Liu, (see: <https://soe.xidian.edu.cn/xkky/kytd/xjcxjxtctd.htm>). Relying on the School of Optoelectronic Engineering of Xidian University and the State Key Laboratory of Mechatronic Manufacturing for High-Performance Electronic Equipment, the team is dedicated to research in areas such as advanced imaging technologies under extreme conditions, as well as real-time detection and tracking of targets. The team currently consists of nearly 10 faculty members and more than 40 master and doctoral students. In recent years, the team has published over 60 papers in high-quality journals, including Light: Science & Applications, Photonics Insights, Opto-Electronics Advances, etc. and been granted more than 50 authorized patents. Major awards include the First Prize of Shaanxi High Education Institutions Technology Research Outstanding Achievements Award, the Second Prize of Henan Provincial Science and Technology Progress Award, the First Prize of Technical Invention Award of the Chinese Society of Optical Engineering.

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