Proceedings of CONF-MLA 2025 Symposium: Intelligent Systems and Automation: AI Models, IoT, and Robotic Algorithms
DOI: 10.54254/2755-2721/2025.LD26879

A Review of High-Precision Ranging Methods Based on Machine Vision

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Abstract. High-precision ranging technology utilising machine vision is a pivotal enabler for fields including robot navigation, autonomous driving, and advanced manufacturing. This paper presents a systematic overview of established machine vision ranging techniques, with particular emphasis on the fundamental principles, performance attributes, and application areas of three methodologies: binocular stereo vision, structured light, and Time-of-Flight (ToF). The paper analyses and contrasts the strengths and weaknesses of each approach: binocular vision, a passive method, offers low cost, but its accuracy and robustness are contingent on environmental texture; structured light achieves high-precision measurement of surfaces lacking texture via active pattern projection, demonstrating considerable advantages in short-range three-dimensional reconstruction; and ToF technology exhibits unique performance capabilities in long-range and real-time depth sensing. Furthermore, this paper explores the crucial role of deep learning in enhancing ranging accuracy and robustness and, with reference to application examples such as robot navigation, forecasts the key trends in future technological developments towards multi-sensor fusion, novel hardware components, and increased intelligent automation.

Keywords: high-precision ranging, machine vision, deep learning

1. Introduction

Across a multitude of sectors including modern industry, robotics, intelligent transport, virtual reality, and scientific research, the need for highly accurate three-dimensional data acquisition of objects or scenes is in ever greater demand. Ranging, as the cornerstone of obtaining three-dimensional information, directly impacts the performance of downstream tasks, such as the robustness of robot navigation [1], the reliability of industrial inspection [2], and the quality of three-dimensional reconstruction [3]. Whilst conventional contact-based ranging methods offer high accuracy, they are limited in many applications by factors such as low efficiency, potential damage to the object under test, or being difficult to implement. Non-contact ranging methods, particularly those employing machine vision, have garnered significant attention due to their flexibility, comprehensive information capture capabilities, and potential for high efficiency [4]. Concurrently, the integration of deep learning with traditional methods has emerged as a leading trend, offering new routes for improving ranging accuracy and robustness, from fundamental image processing and feature matching, to sophisticated system calibration and error correction [3,5].

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This paper presents a systematic review of existing literature concerning high-precision range measurement methodologies based on machine vision. It concentrates on key technical approaches, including binocular stereo vision, structured light, and Time-of-Flight (TOF) techniques, whilst also exploring the use of deep learning to enhance range measurement accuracy. The significance of this research lies in establishing a comprehensive knowledge framework of state-of-the-art technologies for researchers and engineers in relevant domains. By providing a clear comparison of the merits and demerits of different techniques, and by highlighting anticipated future trends, this review offers valuable guidance and points of reference for subsequent technology selection, system development, and algorithm design, thereby facilitating advancements throughout the field.

2. Mainstream machine vision ranging technologies

2.1. Binocular stereo vision

Binocular stereo vision is a passive range-finding technique. As depicted in Figure 1, its fundamental principle involves capturing the same scene from different perspectives using two cameras with a baseline separation, generating image "disparity". A stereo matching algorithm is then used to calculate disparity values for each pixel, which, combined with pre-calibrated camera parameters, enables the reconstruction of three-dimensional depth information using triangulation. However, in challenging environments such as low-light or poorly textured regions, feature point extraction can be problematic, severely impacting matching performance [6]. To overcome this limitation, researchers have proposed combining image enhancement techniques, such as illumination estimation, with deep learning matching networks (e.g., MAHNet), leading to a considerable improvement in range-finding accuracy in difficult conditions [6].

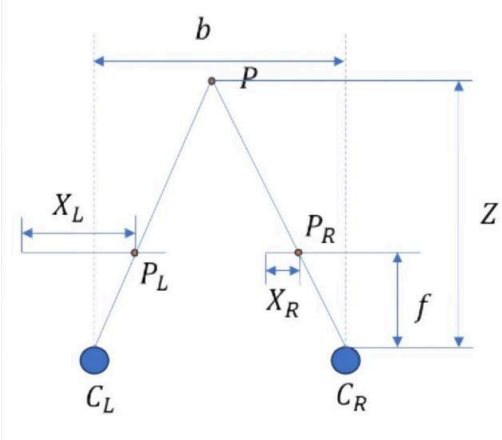

Figure 1. Illustrative diagram of binocular camera distance measurement

In conclusion, the primary advantage of binocular stereo vision lies in its low cost and ability to generate dense depth maps. However, a significant limitation is that its accuracy and robustness are highly sensitive to the richness of scene texture and the effectiveness of the stereo matching algorithm. Consequently, current research is centred on refining calibration and matching algorithms, and integrating them closely with deep learning techniques, in order to address the limitations of this technology in complex environments. The goal is to maintain its relevance and utility in the field of high-precision distance measurement.

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2.2. Structured light

Structured light is an active vision measurement technique, the principle of which is shown in Figure 2. A projector casts pre-designed optical patterns (e.g., light rays or fringes) onto an object. A camera then captures the resulting pattern distortions, caused by the object's surface topography, from a different viewpoint. Finally, three-dimensional coordinates are calculated using triangulation, by analysing the pattern deformation in conjunction with the system parameters [4]. This approach can achieve high-precision measurement at the micrometre scale, but relies heavily on two key elements: accurate system calibration and robust pattern decoding algorithms.

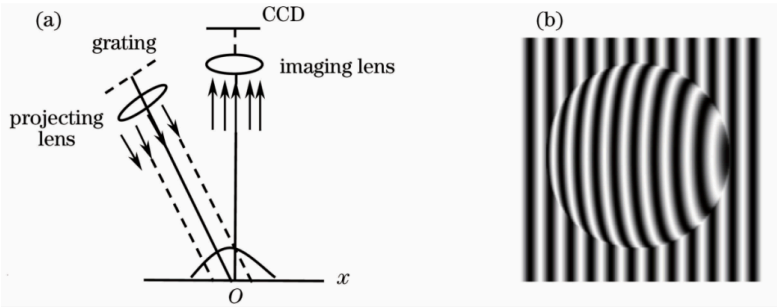

Figure 2. Schematic illustration of structured light imaging

The most significant advantage of this technique is its active measurement characteristic. This allows it to operate independently of the object's inherent texture, enabling high-density, precise three-dimensional reconstruction of smooth or weakly textured surfaces, a feat difficult to achieve with passive vision techniques. However, these advantages come with inherent limitations. Being an active illumination system, it is susceptible to ambient light; strong lighting can overwhelm the projected pattern. Furthermore, it struggles to image highly reflective or transparent surfaces, and is prone to producing artefacts when measuring moving objects. Therefore, owing to its high precision and robustness under controlled conditions, structured light technology finds widespread application in fields such as industrial online inspection, reverse engineering, cultural heritage digitisation, and high-precision robot-assisted grasping [2]. Current research is focused on addressing these limitations by utilising high dynamic range (HDR) imaging, deep learning algorithms, and novel optical elements, such as metasurfaces, to overcome the challenges posed by complex environments and challenging surfaces. These efforts also aim to extend its applicability to wider-ranging areas like underwater environments and large-field-of-view applications [1,7].

2.3. Time-of-Flight (ToF)

Time-of-Flight (ToF) is an active range-finding technique which works by directly measuring the time taken for a light signal to travel from the emitter to the target object and back to the receiver, using the constant speed of light to calculate distance. In contrast to structured light or stereo vision, which rely on geometric relationships to indirectly infer depth, ToF's direct measurement principle allows for the rapid generation of depth maps and exhibits a reduced sensitivity to ambient light and object surface texture. The technology is primarily divided into two categories: direct Time-of-Flight (dToF), which determines distance by measuring the round-trip time of short laser pulses, and indirect Time-of-Flight (iToF), which calculates distance by measuring the phase difference between the emitted and received signals of continuously modulated light. Figure 3 illustrates the differences between iToF and dToF.

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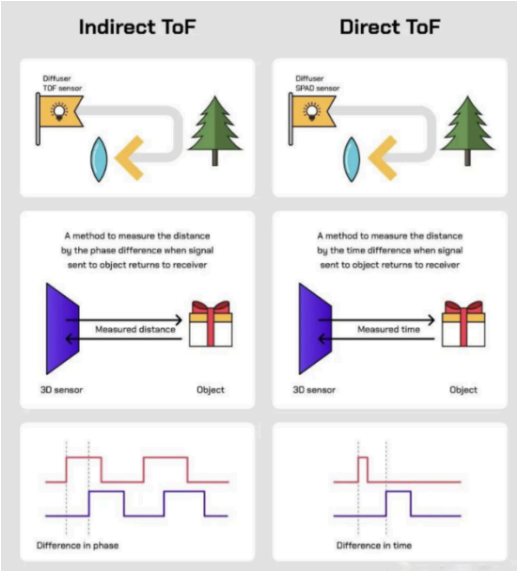

Figure 3. iToF versus dToF comparison

The accuracy of ToF technology is intimately linked to its strengths and weaknesses. Its key advantages lie in its fast response speed, long detection range, and relative immunity to variations in object texture. However, its ultimate accuracy and robustness are subject to a number of challenges. These are primarily governed by the performance of core components and algorithms, such as the reliance of dToF systems on high-precision time-to-digital converters (TDCs) [8], and the linearity of modulated light sources for iToF systems [9]. Furthermore, ToF systems possess inherent limitations, such as the 'range ambiguity' problem, where the unambiguous distance measurable at a single modulation frequency is limited, typically requiring the implementation of multi-frequency switching strategies to overcome this [10].

Owing to its long-range and real-time capabilities, ToF technology holds a pivotal position in fields such as autonomous driving, robot navigation, consumer electronics, and virtual reality. Particularly within automotive LiDAR systems, where demands for detection range and reliability are paramount, ToF represents the dominant technological approach. To satisfy the demands of these advanced applications, current research efforts are increasingly leveraging artificial intelligence methods such as deep learning to address intricate signal processing challenges. For instance, neural networks are being employed to tackle phase unwrapping issues arising from high-frequency modulation [11]. These developments demonstrate that through co-optimisation of hardware and software, ToF technology is progressing towards improved accuracy, enhanced robustness, and greater intelligence.

3. Further advancements in ranging algorithms

3.1. Integration of ranging algorithms with deep learning

Deep learning, owing to its potent non-linear fitting and feature learning proficiencies, has profoundly enhanced all facets of machine vision range finding, emerging as a novel approach for boosting accuracy and robustness. Its utilisation permeates the entire 3D perception workflow. During data pre-processing, deep learning can facilitate image enhancement, such as retrieving image details in low-light conditions, thus providing higher-quality input for subsequent processes [6]. Within the core ranging algorithm, its impact is even more pronounced. In the context of

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binocular vision, from acquiring robust feature descriptors to constructing end-to-end networks that directly predict disparity, deep learning has comprehensively revolutionised stereoscopic matching techniques [6]. For active technologies like Time-of-Flight (ToF) and structured light, deep learning is deployed to tackle intricate physical and signal processing issues, for example, high-frequency phase unwrapping [11], sensor noise modelling [3], and the intelligent optimisation of system parameters [12].

Despite substantial progress, the application of deep learning methods continues to face challenges, including reliance on extensive labelled datasets, limited model interpretability, and demanding computational resource requirements. Consequently, future research will concentrate on exploring more efficient and lightweight network models to cater to the needs of embedded platforms [13], and investigating how to deeply integrate the powerful perceptual capabilities of deep learning with the theoretical completeness of traditional geometric methods, with the aim of surpassing the current performance limitations of existing visual ranging technologies.

3.2. Application examples in robot path planning and navigation

High-precision ranging forms the cornerstone for robots achieving autonomous navigation, environmental awareness, and intelligent operation. Three-dimensional depth information, acquired either through passive or active vision, provides the foundation for robots to understand and model their surrounding physical world. Machine vision ranging technologies, with their non-contact nature and rich data output, play a crucial role in this domain. Different visual ranging solutions, owing to their inherent characteristics, are suited to different robotic application scenarios.

In robot navigation, binocular stereo vision is widely employed due to its cost-effectiveness, with research focusing on enhancing the precision of depth perception by improving calibration accuracy to meet increasingly advanced demands, from basic obstacle avoidance to intricate manipulation [6]. For challenging environments such as those with sparse textures or underwater conditions, structured light techniques offer advantages. Existing studies have successfully achieved high-precision dense mapping and safe collision avoidance for underwater robots by designing active optical vision systems that integrate multi-source information and by establishing bespoke refraction and motion compensation models, thus validating their potential in complex, dynamic, and specialised environments [1]. For long-range and high-speed dynamic scenarios, Time-of-Flight (ToF) technology, exemplified by LiDAR, takes centre stage. Its long-range and high-precision characteristics are key to enabling all-weather real-time environmental perception for autonomous vehicles, providing centimetre-level ranging accuracy and detection capabilities spanning hundreds of metres for Level 4 and above autonomous driving [14].

In summary, high-precision ranging technology functions as the “eyes” of robots, granting them the capability to perceive the three-dimensional world. Currently, deep learning is deeply integrated into various visual ranging algorithms, from calibration optimisation to data processing, comprehensively enhancing the navigation and operational performance of robots in complex environments. Looking ahead, multi-sensor fusion approaches that combine the strengths of different technologies, along with bespoke and intelligent solutions tailored to specific application scenarios, will represent the most important development avenues in this field.

4. Discussion

This paper provides an overview of high-precision machine vision ranging techniques, focusing on binocular stereo vision, structured light, and Time-of-Flight (ToF). The research highlights inherent

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trade-offs between these approaches: binocular stereo vision, a passive technique, offers low cost but its accuracy depends on environmental textures and the efficacy of matching algorithms. Conversely, active techniques like structured light and ToF circumvent this dependency by emitting known signals, offering distinct advantages in short-range, high-precision measurements and long-range, real-time detection, respectively. Nevertheless, regardless of the specific technology, improving performance requires addressing shared challenges such as precise system calibration, adaptability to complex environments, and the suppression of noise and errors.

In recent years, deep learning has emerged as a pivotal force in advancing this field. Its applications in feature matching, data completion (in-painting), and error compensation have markedly improved the accuracy and robustness of current ranging solutions. Looking to the future, multi-sensor fusion represents a crucial strategy for overcoming the limitations of individual technologies. By integrating different vision sensors [15], or by incorporating non-vision information, such as from an IMU [1], systems can achieve reliable, high-precision ranging in more intricate environments. Within this trend, deep learning is set to play an increasingly vital role.

5. Conclusion

This research aimed to provide a systematic review of high-precision range-finding technologies based on machine vision. The analysis revealed that, whilst mainstream technologies such as binocular vision, structured light, and Time-of-Flight (ToF) each possess their own advantages, they also suffer from inherent and insurmountable limitations. The incorporation of deep learning has emerged as a crucial driver for improving range-finding accuracy, robustness, and environmental adaptability. Theoretically, this research contributes to the existing body of knowledge by systematically outlining the evolution of these technologies, from traditional geometric methods to modern deep learning models. The findings clearly identify current cutting-edge directions and core challenges, providing new evidence for understanding the patterns of technical iteration in this field, and addressing a gap in the comprehensive overview of the technological development pathway. For areas such as robotics, autonomous vehicles, and industrial automation, this research holds significant practical value, and the comparative analysis of different technical solutions can furnish engineers with a clear decision-making framework during project development and solution selection.

However, this research does acknowledge certain limitations. Its principal weakness resides in the breadth of the analysis: owing to the rapid pace of technological advancement, this review has not encompassed all nascent range-finding methods, potentially influencing the comprehensiveness of the conclusions to some degree. To mitigate this, future research could focus on more detailed, thematic explorations of specific emerging technologies or specific application scenarios.

In conclusion, this research offers fresh insights into the domain of high-precision machine vision range-finding, underscoring the importance of deep learning and multi-sensor fusion as pivotal elements in future development. By elucidating the current technological landscape and prospective trends, this study paves the way for the realisation of three-dimensional perception systems exhibiting enhanced precision and robustness.

References

[1] Ou, Y., Fan, J., Zhou, C., Cheng, L., & Tan, M. (2024). Water-MBSL: Underwater movable binocular structured light-based high-precision dense reconstruction framework. IEEE Transactions on Industrial Informatics, 20(4), 6142–6154. https: //doi.org/10.1109/tii.2023.3342899

DOI: 10.54254/2755-2721/2025.LD26879

[2] Xi, C., Liu, S., Chang, S., Dong, Y., Zhong, W., Jiang, X., & Lu, W. (2025). Enhancing accuracy of line-structured light sensor for narrow weld gap measurement. IEEE Transactions on Instrumentation and Measurement, 74, 1–10. https: //doi.org/10.1109/tim.2025.3553256
[3] Afzal Maken, F., Muthu, S., Nguyen, C., Sun, C., Tong, J., Wang, S., Tsuchida, R., Howard, D., Dunstall, S., & Petersson, L. (2025). Improving 3D reconstruction through RGB-D sensor noise modeling. Sensors, 25(3), 950. https: //doi.org/10.3390/s25030950
[4] Ding, S., Zhang, X., Yu, Q., & Yang, X. (2017). Review of non-contact 3D reconstruction measurement methods. Laser & Optoelectronics Progress, 54(7), Article 0700003.
[5] Chen, H., Li, H., Liu, G., & Wang, Z. (2024). A novel simulation method for 3D digital-image correlation: Combining virtual stereo vision and image super-resolution reconstruction. Sensors, 24(13), 4031. https: //doi.org/10.3390/s24134031
[6] Zhang, J., Li, J., Liu, H., Wang, H., Yi, D., & Li, Q. (2024). Robust distance measurement using illumination map estimation and MAHNet in underground coal mines. Measurement Science and Technology, 35(8), 086013. https: //doi.org/10.1088/1361-6501/ad25e0
[7] Kim, G., Kim, Y., Yun, J., Moon, S.-W., Kim, S., Kim, J., Park, J., Badloe, T., Kim, I., & Rho, J. (2022). Metasurface-driven full-space structured light for three-dimensional imaging. Nature Communications, 13(1), Article 4586. https: //doi.org/10.1038/s41467-022-32117-2
[8] Koerner, L. J. (2021). Models of direct time-of-flight sensor precision that enable optimal design and dynamic configuration. IEEE Transactions on Instrumentation and Measurement, 70, 1–9. https: //doi.org/10.1109/tim.2021.3073684
[9] Yang, J., Meng, Y., Hu, X., Yang, T., Wang, Z., Jia, D., & Ge, C. (2024). High-ranging-precision FMCW LiDAR with adaptive pre-distortion of current injection to a semiconductor laser. Journal of Lightwave Technology, 42(6), 1870–1876. https: //doi.org/10.1109/jlt.2023.3328575
[10] Hanto, D., Pratomo, H., Rianaris, A., Setiono, A., Sartika, S., Syahadi, M., Pristianto, E. J., Kurniawan, D., Bayuwati, D., Adinanta, H., Suryadi, S., Hadi, M., Mulyanto, I., Husdi, I. R., Ula, R. K., Widiyatmoko, B., & Kurniawan, E. (2023). Time of flight lidar employing dual-modulation frequencies switching for optimizing unambiguous range extension and high resolution. IEEE Transactions on Instrumentation and Measurement, 72, 1–8. https: //doi.org/10.1109/tim.2023.3235450
[11] Baek, S.-H., Walsh, N., Chugunov, I., Shi, Z., & Heide, F. (2023). Centimeter-wave free-space neural time-of-flight imaging. ACM Transactions on Graphics, 42(1), 1–18. https: //doi.org/10.1145/3522671
[12] Ren, J., Guan, F., Wang, T., Qian, B., Luo, C., Cai, G., Kan, C., & Li, X. (2022). High precision calibration algorithm for binocular stereo vision camera using deep reinforcement learning. Computational Intelligence and Neuroscience, 2022, 1–10. https: //doi.org/10.1155/2022/6596868
[13] Zou, C., Ou, Y., Zhu, Y., Martins, R. P., Chan, C.-H., & Zhang, M. (2024). 6.8 a 256×192-pixel 30fps automotive direct time-of-flight LiDAR using 8× current-integrating-based TIA, hybrid pulse position/width converter, and intensity/CNN-guided 3D inpainting. 2024 IEEE International Solid-State Circuits Conference (ISSCC), 114–116. https: //doi.org/10.1109/isscc49657.2024.10454461
[14] Bai, Y., Tang, W., Xu, S., Yang, Z., Lü, M., Yu, C., Gao, J., Zheng, J., Liu, Y., & Qin, Y. (2020). A real-time high-precision ranging method for laser imaging radar with large dynamic range at close range. Infrared and Laser Engineering, 49(S2), 118–123.
[15] Yin, W., Feng, S., Tao, T., Huang, L., Trusiak, M., Chen, Q., & Zuo, C. (2019). High-speed 3D shape measurement using the optimized composite fringe patterns and stereo-assisted structured light system. Optics Express, 27(3), 2411. https: //doi.org/10.1364/oe.27.002411