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Review of in-motion extended-range 3D optical measurement for industrial applications

Luyao Ma¹, Jigui Zhu², Linghui Yang², Nan Gao¹, Zhaozong Meng¹, Yubo Ni¹ and Zonghua Zhang^{1,*}

Abstract: Acquiring three-dimensional (3D) shape information plays a vital role in the industrial field, with optical methods being widely adopted. For industrial surfaces that exhibit continuous extension, such as trains, tracks, tunnels, and production lines, performing in-motion extended-range 3D shape measurement has become an important requirement due to its high efficiency, excellent continuity, and strong adaptability to relevant scenes. This paper overviews the state-of-the-art in-motion extended-range 3D optical metrology for industrial applications. It outlines the measurement procedure and identifies key challenges. A comprehensive survey of optical methods for 3D point cloud generation and extension is presented, along with techniques for controlling micro and macro accuracy during continuous motion and strategies for ensuring data completeness in a single dynamic scan. The paper concludes with insights into future development directions.

Keywords: 3D shape; optical measurement; extension; motion

Introduction

Three dimensional (3D) shape contains rich spatial structural information and can fully characterize the macroscopic shape, local features, and microscopic details of an object^{1,2}. It is one of the most important geometric parameters in both fundamental scientific research and industrial applications^{3,4}. Optical-based 3D shape measurement techniques are widely used due to their advantages of non-contact operation, high accuracy, and high speed⁵.

In industrial applications, there is a distinct category of surfaces characterized by one dimension being substantially greater than the other two, forming a characteristic extended-range geometry. Such structures are frequently encountered across various engineering equipment, ranging from large-scale infrastructures like high-speed train bodies^{6,7}, tunnel linings^{8–10}, and railway tracks^{11–13}, to components in typical industrial manufacturing scenarios such as conveyor belt^{14,15}. The “extended range” concept entails two essential aspects. First, it denotes significant length. Target surfaces may extend from tens of meters to several kilometers (e.g., trains, rails, and tunnels) or be treated as virtually infinite in one direction due to their mechanical design (e.g., conveyor belts and production

lines). Second, it also implies surface continuity, meaning the surface spans a great distance seamlessly and without interruption. To scan long, continuous surfaces and achieve extended-range measurement, motion plays a critical role. Continuous movement not only improves measurement efficiency over large distances but also avoids local point cloud gaps associated with static discrete measurement. In practice, optical methods demonstrate distinct advantages in terms of efficiency, accuracy, and non-contact operation. Therefore, the concept of in-motion extended-range 3D optical measurement is proposed.

Solving this measurement problem entails notable challenges. Take the well-known domain of large-scale metrology as an example, key considerations typically include: 1) point cloud generation and registration, 2) micro and macro accuracy control, and 3) handling of complex optical or curvature properties. Given the universal goals in the field of measurement, in-motion extended-range 3D optical measurement similarly considers these categories of challenges. Nevertheless, due to the unique nature of the technical implementation—where the dynamic extension property represents a measurement paradigm distinct from conventional approaches—the related challenges exhibit markedly different characteristics.

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First, regarding point cloud generation and stitching, the conventional approach of static measurement and intermittent stitching (which separates measurement from motion) is no longer sufficient¹⁶. Instead, it is essential to achieve dynamic generation of point clouds and continuous seamless stitching coupled with motion information^{17–20}. This process requires careful consideration and trade-offs among key parameters such as field of view, spatial resolution in the tangential and normal directions of the scanning trajectory, and motion speed. Commonly adopted optical methods include time-of-flight (ToF) laser scanning²¹, laser triangulation scanning^{22,23}, area-scan vision measurement^{24–26}, and line-scan vision measurement^{27–29}.

Second, the measurement process is deeply coupled with motion, which is inherently uncertain and susceptible to interference in industrial environments. Thus, controlling accuracy becomes particularly challenging. This issue must be addressed at both the micro and macro levels. For micro-scale accuracy control, it is necessary to achieve micrometer to millimeter-level accuracy for arbitrary local features within an extended 3D volume under dynamic conditions. For macro-scale accuracy control, sufficiently large (hundred-meter to kilometer-scale) or theoretically extensible global constraints must be established during long-distance system movement.

Third, industrial surfaces with extended-range geometry inevitably contain local regions of complex optical properties or curvature^{4,30}. This poses a particular challenge, often resulting in the partial loss of 3D shape data. Nevertheless, as the measured surface extends over a long distance, reverse movement or repeated scanning must be strictly avoided, requiring complete 3D scanning in a single pass. Notably, this is especially critical in scenarios such as inspection on a continuously operating production line or tunnel monitoring conducted alongside normal traffic flow,

where motion cannot be stopped or reversed. Consequently, ensuring the completeness of 3D shape data is particularly challenging.

This paper presents a review of pertinent research, and the organization is shown in Fig. 1. First, it offers a concise overview of the workflow for in-motion extended-range 3D measurement. Then, several key issues with related research work are elaborated: the paper categorizes different 3D point cloud acquisition techniques, comparing their respective characteristics; it provides a detailed discussion of micro and macro accuracy control strategies during motion-based extended-range measurement; it analyzes approaches to ensure complete 3D data acquisition under single dynamic scanning conditions when facing complex surface optical properties and curvatures. Subsequently, the paper outlines promising development directions and ongoing challenges for future work. The last section presents the conclusion.

Procedure of in-motion extended-range 3D measurement

The measurement process begins with calculating point coordinates within the sensor coordinate frame. The sensor typically captures data of a single profile in each measurement, as this is easier to implement in motion state. The continuous motion, in turn, enables the coverage of the entire surface.

By applying suitable algorithms, each point within the profile is accurately computed, resulting in the generation of a profile point cloud. Common optical measurement techniques primarily include laser scanning and vision-based methods, which can be further classified into ToF laser scanning, laser triangulation scanning, area-scan vision measurement, and line-scan vision measurement. The individual profile point clouds are then sequentially

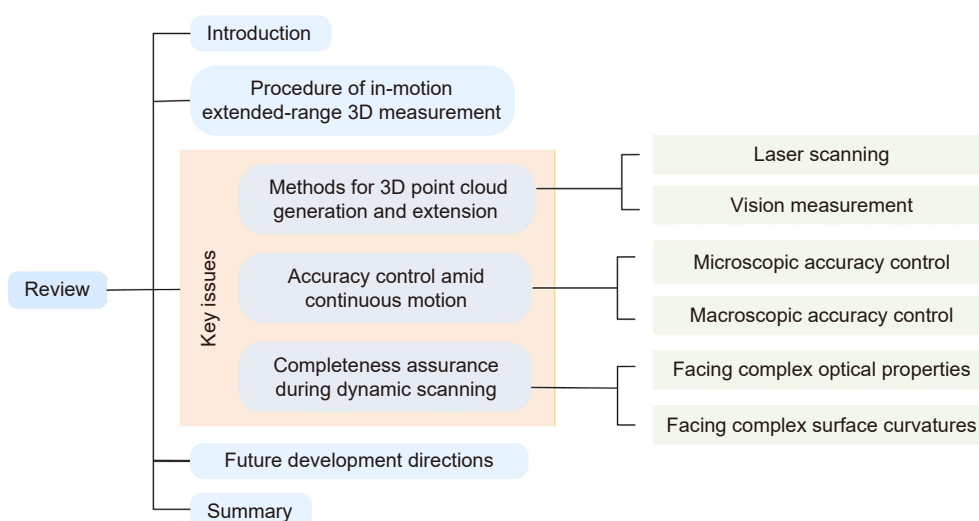


Fig. 1 | The organization of the paper.

aligned and stitched together in world coordinate frame using motion information to form an extended-range continuous 3D shape. Motion data can be acquired through various means, such as pre-programmed devices (e.g., guide rails or robots) operating at defined speeds along known trajectories, or external positioning systems and markers that provide continuous pose updates. The profile point clouds are fused with corresponding motion data at each timestamp using spatio-temporal alignment algorithms.

During the measurement process, particular attention must be paid to key performance indicators such as the field of view in sensor direction, the scanning speed in trajectory direction, and the resolution in both directions. Furthermore, motion-induced uncertainties—especially prevalent in complex industrial environments—pose significant challenges to maintain measurement accuracy within a dynamically extending spatial domain. Additionally, ensuring data completeness during a single dynamic scan is critical, particularly when capturing intricate industrial surfaces. The overall schematic diagram is illustrated in Fig. 2.

Methods for 3D point cloud generation and extension

Laser-based and vision-based methods, as prevalent optical techniques, employ various ranging methods to obtain the point coordinates in the sensor coordinate system, and the sensors are integrated with mobile carriers—such as inspection vehicles and robots—to extend the measurement range and address diverse industrial needs. Despite the diversity of methods, the following requirements must be met: 1) generation of point clouds in dynamic conditions, and 2) continuous range extension through motion-fused stitching. Figure 3 demonstrates the above requirements. Building upon these common prerequisites, further analysis of other key indicators such as resolution and motion speed is conducted to tailor solutions based on their respective characteristics for diverse engineering applications.

Laser scanning

Laser scanning technology is characterized by highly concentrated energy and strong interference resistance, making it particularly suitable for scanning large-scale infrastructures such as massive tunnels. It also remains effective in close-range acquisition scenarios and demonstrates good adaptability to reflective surfaces. Since no complex image processing is required, laser-based methods are generally easy to implement with fast data processing speeds. Nevertheless, the underlying point-by-point scanning mechanism inherently imposes trade-offs among the field of view, scanning speed, and resolution. Other practical limitations include helical trajectory distortion during motion and the absence of texture information in the acquired data.

Time-of-flight laser scanning

The ToF method is well-suited for large-scale distance measurement applications^{31,32}. As shown in Fig. 4, its fundamental principle involves calculating the distance to target objects by measuring either the time delay or the phase shift between the emitted laser signal and its returning reflection^{33,34}. The system primarily employs two approaches: pulse-based direct measurement and phase-based indirect measurement. The pulse-based method features a simpler system architecture and easier implementation, whereas the phase-based approach offers higher accuracy. Owing to its capability for large-area data acquisition, ToF laser scanning is commonly deployed on inspection vehicles capable of continuous movement, thereby enabling progressive extension of the measurement range over long distances^{19,35}. For instance, in tunnel inspection, the fusion of circumferential scanning with the vehicle's forward motion generates a helical scan path. This path extends dynamically with movement, thereby enabling the progressive coverage of large-scale tunnel surfaces.

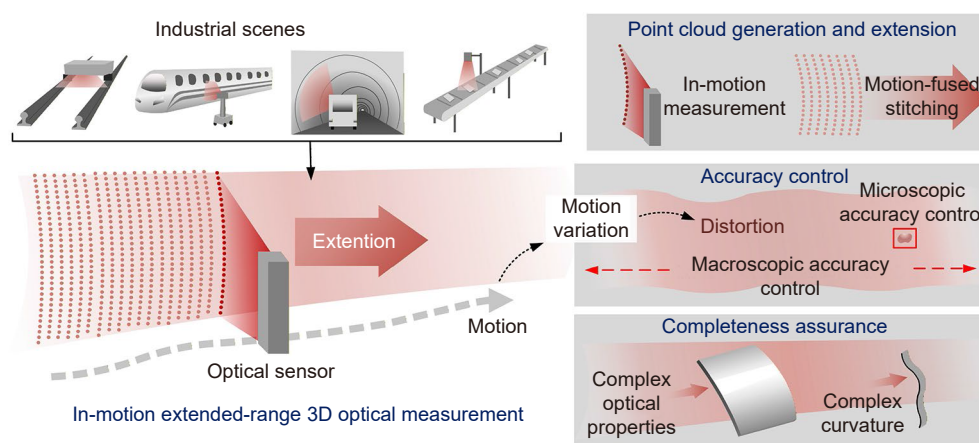


Fig. 2 | Overall schematic diagram of in-motion extended-range 3D measurement.

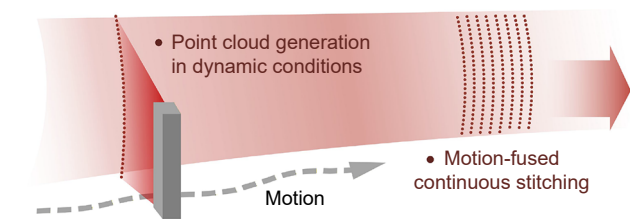


Fig. 3 | Specific requirements for 3D point cloud generation and extension.

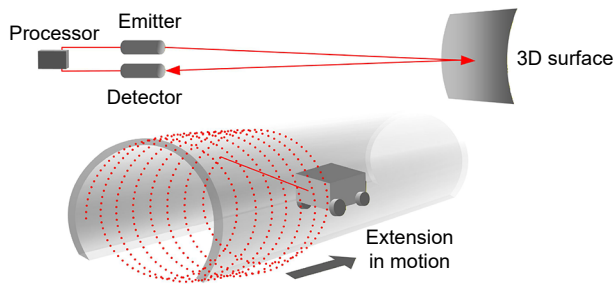


Fig. 4 | Schematic diagram of ToF laser scanning.

This technology is widely applied in scenarios such as in-motion tunnel inspection and road surface monitoring. It operates synchronously with traffic flow, minimizing disruption to normal transportation while significantly enhancing inspection efficiency. However, due to its inherent point-by-point scanning mechanism, the acquired data are spatially discrete with low point cloud density, making it difficult to support fine-grained detailed detection. Moreover, when circumferential point-by-point acquisition is performed during continuous system movement, a helical scanning trajectory is often generated^{10,36}. Consequently, high-precision motion data must be incorporated to provide meticulous compensation and ensure the geometric accuracy of the point clouds.

Laser triangulation scanning

Laser triangulation utilizes the principles of optical reflection and geometric similarity of triangles during light propagation^{23,37}. It establishes a geometric similarity relationship and enables displacement calculation of the target by analyzing angular and edge correlations. Owing to the compact physical size of the sensor, this technique is particularly suited for close-range measurement applications, with accuracy reaching the micrometer level. The sensor typically incorporates a rotating mechanism to capture point cloud data along a contour line of the measured object. Relative applications include the flying-spot laser scanning technique developed by Zhang²² and the commercial DLR Laser Range Scanner. To enable in-motion continuous extension of the measurement range, the sensor is commonly integrated with robotic arms or incorporated into handheld scanning systems equipped with positioning

modules for flexible operation. The schematic diagram is demonstrated in Fig. 5.

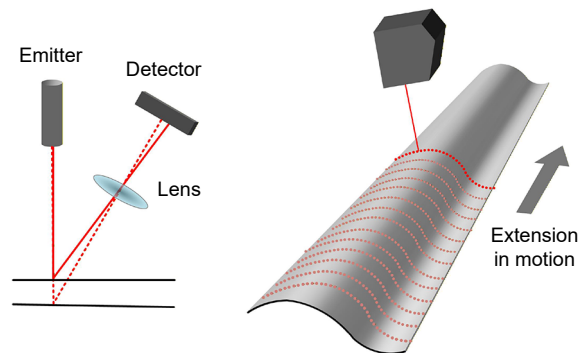


Fig. 5 | Schematic diagram of laser triangulation scanning.

Similarly constrained by the point-by-point scanning mechanism, this method exhibits a narrow field of view under high-resolution requirements and relatively low motion speed during measurement range extension. Nevertheless, owing to its exceptional accuracy, laser triangulation scanning remains widely adopted in industrial inspection applications. For example, it can be employed for dynamic scanning along paths of welds or grooves, enabling high-precision evaluation of 3D shape quality.

Vision measurement

Vision measurement systems typically employ cameras and projectors. The camera imaging sensors capture the structured light stripes or patterns projected onto the object surface, and the 3D point coordinates are calculated through image matching and triangulation. Since a camera captures multiple pixels simultaneously during a single exposure, the non-point-by-point measurement mode is highly efficient. However, camera-based methods also face limitations. The area-scan vision-based methods show constraints on acquisition frequency, while the line-scan vision-based methods face challenges in image matching and light source design.

Area-scan vision measurement

Area-scan vision measurement systems typically utilize two-dimensional (2D) imaging sensors (CCD or CMOS)³⁸. Widely used techniques include passive vision measurement^{39–42}, area-structured light measurement^{43–45}, and line-structured light measurement. However, passive vision approaches depend on natural surface textures or artificially applied speckle patterns, while area-structured light methods generally require multi-frame projection under an ideal and static conditions. Additionally, both techniques tend to generate local point clouds with overlapping transitions or gaps. Consequently, these methods are generally

not well-suited for in-motion measurement of industrial surfaces with continuous extension. Zhang have conducted comprehensive research and provided a systematic review of single-shot area-structured light measurement techniques⁴⁶. These methods achieve local point cloud acquisition through a single capture and remain unaffected by motion. Future integration with advanced acquisition interval control technologies could enable continuous point cloud expansion during movement while maintaining high continuity. It will play a significant role for in-motion extended-range 3D measurement in the future.

Currently, a more suitable measurement solution is the line-structured light method^{47,48}, as shown in Fig. 6. The projector emits a laser plane, which forms a laser stripe on the surface of the measured object. The area-scan camera captures a 2D image containing the stripe in a single acquisition. Accurate matching of the camera and projector is achieved through stripe center extraction and epipolar constraint. By combining the matching results with the calibrated parameters of the system, the 3D coordinates of each point can be calculated. Unlike point-by-point laser scanning, the vision-based method can simultaneously obtain coordinates of multiple points, thereby improving the measurement efficiency. Meanwhile, the single-frame measurement of profile point cloud is inherently immune to motion, making it a more suitable method for dynamic scanning compared to most area-structured light approaches. By integrating synchronized triggering technology, image capture and motion data are temporally aligned. This alignment ensures that each profile point cloud is registered with its corresponding motion state, thereby extending the measurement range along the moving path.

However, this method also has certain limitations. The 2D images contain a significant amount of redundant data unrelated to the laser stripe, resulting in a relatively low data utilization rate. Consequently, the acquisition frequency of the camera is limited, restricting the extension speed of the point cloud in the direction of motion, or making it difficult to maintain spatial resolution along the motion trajectory under high-speed conditions.

This method is widely used in the inspection of infrastructure such as rails and pipelines for its multi-point simultaneous measurement and ease of implementation. In pipeline inspection applications, special annular line-structured light can be designed and employed due to its suitability for such specific scenarios⁴⁹.

Line-scan vision measurement

Unlike area-scan cameras, line-scan cameras acquire images exclusively along a single dimension. This dimension-reduced imaging approach achieves extreme performance in both resolution (up to 8192 pixels) and acquisition frequency (from tens to hundreds of kHz)^{50,51}. When working with high-speed structured light projection device, line-scan cameras can easily realize high-frequency acquisition of dense point clouds in motion^{28,52,53}. In contrast to laser scanning methods, this method retains the advantage of simultaneous multi-point measurement characteristic inherent to vision-based systems. Compared to area-scan vision approach, this method offers higher acquisition rates, thereby accelerating the extension of 3D shapes, while maintaining excellent resolution in both the tangential and normal directions of the scanning trajectory. From the perspective of the underlying measurement mode, line-scan vision measurement stands out as the optimal optical solution for in-motion extended-range 3D measurement applications. The measurement schematic diagram is illustrated in Fig. 7. The matching of a line-scan camera and a projector requires the projection with pattern variation in a single direction and one-dimensional (1D) image analysis of deformed patterns. The generation and extension of point clouds rely on subsequent triangulation and motion-fused point cloud stitching, similar to the area-scan vision measurement with line-structured light.

Nevertheless, line-scan vision methods are still in a developmental stage, with several challenges yet to be resolved. Achieving high-frequency acquisition with line-scan cameras demands structured light projectors capable of high brightness and sufficient switching frequency to

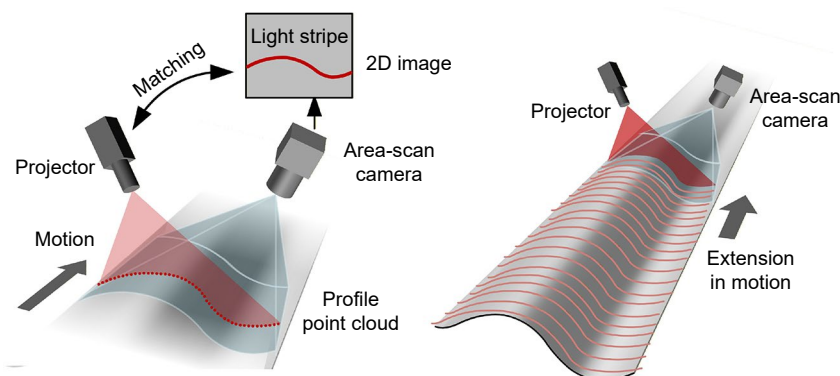


Fig. 6 | Schematic diagram of area-scan vision measurement.

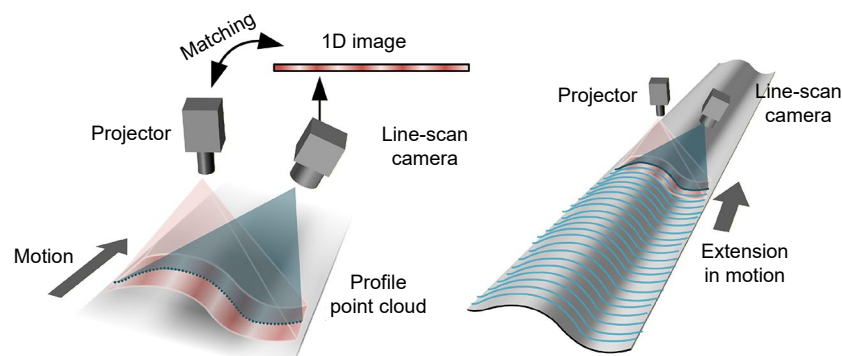


Fig. 7 | Schematic diagram of line-scan vision measurement.

capture high signal-to-noise ratio images within extremely short exposure times. Although projection technology based on digital micromirror device (DMD) chips offers a promising approach^{54–56}, the luminous intensity and switching frequencies remain inadequate. The 1D image matching also represents key challenges, particularly in reducing mismatches. Additionally, due to the difficulty in establishing correlations between the 1D images or profile point clouds acquired by line-scan cameras, controlling stitching accuracy remains a critical challenge, which will be discussed later. Therefore, although line-scan image-based inspection⁵⁰ has been implemented in applications such as assembly lines or tunnels, 3D shape measurement utilizing line-scan cameras remains an ongoing area of research.

Table 1 summarizes the characteristics of typical optical methods for in-motion extended-range 3D measurement. An analysis of their strengths and weaknesses can provide guidance for selecting suitable solutions across different application scenarios.

Accuracy control amid continuous motion

The process of 3D point cloud measurement is coupled with continuous motion. In complex industrial environments, the motion state is often uncontrollable, leading to nonlinear trajectories, non-uniform velocities, and instantaneous dynamic disturbances. These factors adversely affect

both microscopic details and macroscopic structures in measured 3D shapes. For example, nonlinear trajectories may cause misalignment between consecutive profile point clouds, leading to distortions in the global model and local structure. Non-uniform velocities can result in inconsistent sampling density, causing macro-scale stretching or compression as well as the degradation of micro-scale structure in sparsely sampled regions. Instantaneous dynamic perturbations introduce high-frequency noise, compromising the accuracy of micro-scale feature representation. As a result, achieving accuracy control amid continuous motion has emerged as a significant research focus.

Microscopic accuracy control

Microscopic accuracy primarily focuses on the reconstruction of detailed features such as cracks in tunnels or weld seams. As depicted in Fig. 8, the process entails three key requirements: 1) ensuring controllable accuracy for any local detail within large-scale, extended point clouds, 2) achieving high precision, typically at micrometer to millimeter levels, and 3) maintaining accuracy in continuous motion.

Common methods can generally be divided into three categories: sensor-based approaches, point cloud shape-based methods, and image feature-based techniques. Among sensor-based methods, the simplest approach

Table 1 | Characteristics of typical optical methods for in-motion extended-range 3D measurement.

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Methods	Strengths	Weaknesses
Time-of-flight laser scanning	Concentrated energy and large scanning range Suitable for massive, long-range infrastructures Easy implementation	Spatially discrete point clouds caused by point-by-point measurement mode
Laser triangulation scanning	Strong anti-interference capability owing to concentrated energy Easy implementation	Limited observation distance Restricted field of view caused by point-by-point measurement
Area-scan vision measurement	A gain in efficiency through multi-point simultaneous measurement Easy matching with line structured light	Limited acquisition frequency Difficult to achieve rapid and high-resolution scanning in motion
Line-scan vision measurement	Multi-point simultaneous measurement Extremely high frequency and high resolution Rapid generation and extension of dense point clouds	Challenging 1D image matching Lack of compatible structured light sources Difficult extension accuracy control

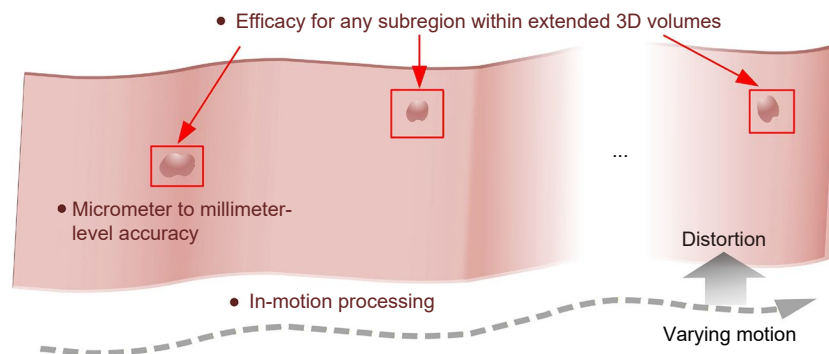


Fig. 8 | Specific requirements for microscopic accuracy control.

utilizes devices such as encoders or odometers to achieve detail correction under dynamic conditions⁵⁷. For example, Li et al. utilized an encoder to align successive laser scans of tunnel cross-sections¹⁰. Meanwhile, interpolation of encoder data was also employed to corrected motion-induced spiral distortions of each laser-scanned profile. The errors for measuring 37 ring slices are all within 3 mm, with an average of 1.3 mm. Similarly, Hu et al. incorporated an encoder into their in-motion continuous 3D scanning system based on line-scan cameras to mitigate motion-related distortions in 3D shape⁵⁸, as shown in Fig. 9. Nevertheless, this category of methods is fundamentally constrained by the encoder's performance and the limited degrees of freedom available for correction, thus it still requires further development.

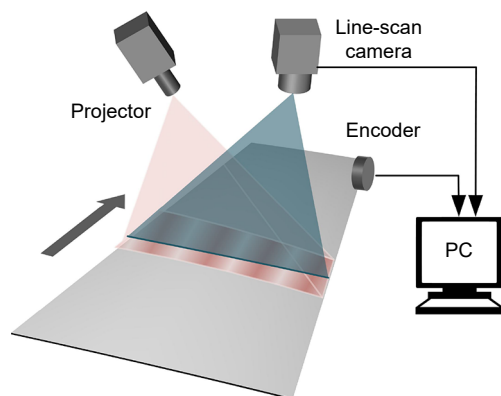


Fig. 9 | In-motion line-scan measurement with an encoder.

Another widely adopted strategy utilizes point cloud shape information. It should be noted that since the measurement process entails in-motion continuous acquisition of profile point clouds, conventional registration techniques for regional point clouds⁵⁹—such as the iterative closest point (ICP) algorithm—become inadequate⁶⁰. Zhan et al. installed two line-structured light sensors underneath a tunnel inspection vehicle^{8,61,62}, as shown in Fig. 10. By identifying feature points within the profiles of the left and

right rail heads, they estimated the real-time pose of the vehicle and corrected point cloud stitching errors resulting from vehicle vibrations. In tunnel 3D scanning experiments, the root mean square error is about 0.8 mm⁸. This approach, however, depends on prior knowledge of the distance between the two rail heads. Similarly, several methods leverage known morphological features of tracks or pipelines. For example, Liu et al. employed the centers of the large and small circular arcs of rail waists—extracted from the rail profile point cloud—as control points to quantify positional deviations⁶². Figure 11(a) demonstrates the schematic diagram. Gunatilake et al. utilized the inherent cylindrical geometry of pipelines to estimate the orientation of profile point clouds and perform pose correction⁴⁹, as illustrated in Fig. 11(b). The achieved accuracy is at the millimeter level, which is sufficient to meet the requirements for liner defect quantification. However, these methods depend on certain known geometric information of the measured surfaces or surrounding objects for reference, which restricts their general applicability. Furthermore, because the reference shapes often exhibit repetition along a certain direction, the degrees of freedom for correction are limited, making it difficult to achieve comprehensive accuracy control. To minimize reliance on known shape parameters, Lim's method employed an optical technique to generate two laser projections, ensuring that each projected position overlaps with the previous one when the measured surface moves⁶³. By analyzing two successive profile point clouds, it is possible to estimate and compensate for the object's vertical vibration. A schematic of the method is provided in Fig. 12. The approach achieves 96.3% reduction in the root mean square error.

Methods based on image features are frequently used in area-scan camera systems with line-structured light measurement. These techniques capture not only the laser stripe but also surrounding texture information in the same image, enabling correspondence establishment between adjacent profiles through the shared observation of surrounding features. Commercial systems such as Creaform's HandySCAN 3D exemplify this approach. A limitation of such systems, however, is the need to attach

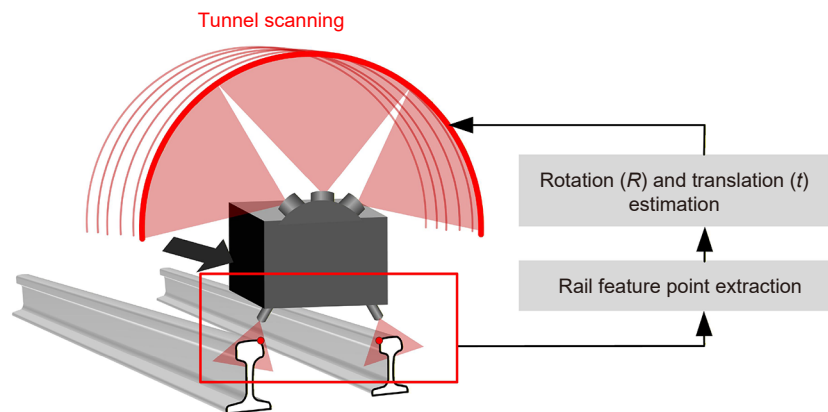


Fig. 10 | Tunnel scanning accuracy control based on rail profile geometry under vibration conditions. Figure reproduced with permission from: ref.⁸, Multi-disciplinary Digital Publishing Institute.

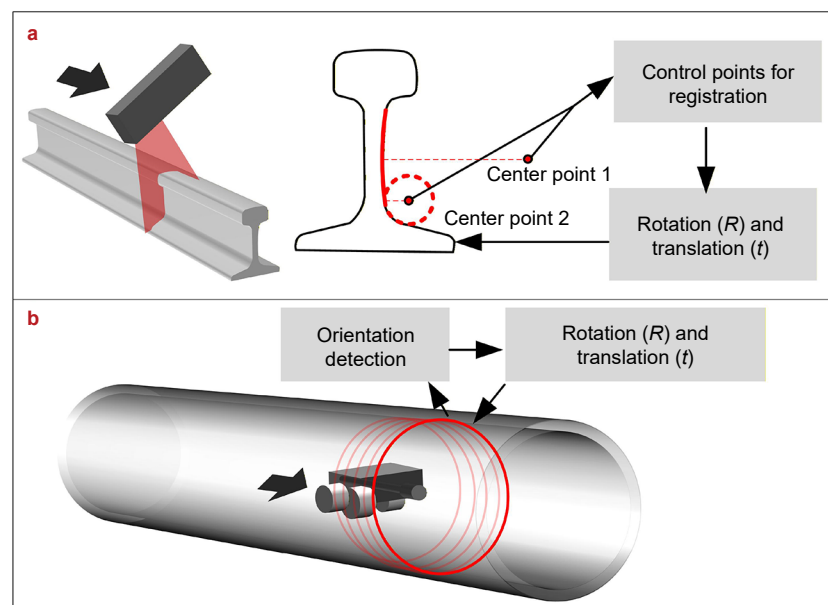


Fig. 11 | Point cloud registration correction based on priori shape information of the extended surface. (a) Utilizing the priori knowledge of the rail cross-section. (b) Leveraging priori information of the pipeline cross-section.

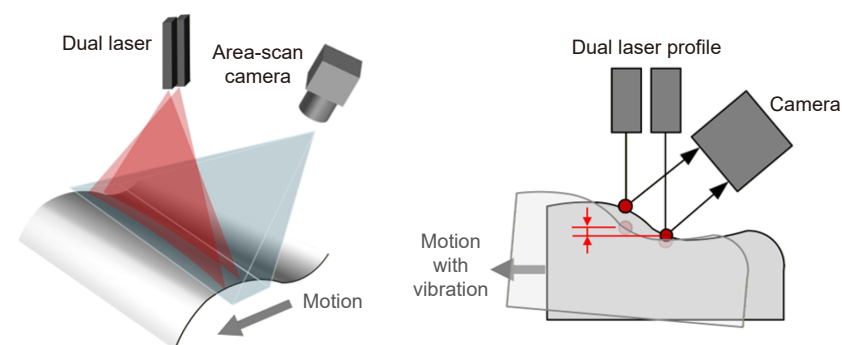


Fig. 12 | Vibration compensation during dynamic scanning based on one-body dual laser profile measurement.

control points to the target surface—a process that is impractical for surfaces with long-distance extension⁶⁴. Yin et al. addressed this issue by developing a method that uses natural surface features for image matching and point cloud profile registration⁶⁵, eliminating the dependency on artificial markers, as can be seen in Fig. 13. The method demonstrates a root mean square error of about 0.4 mm. For line-scan camera systems, which provide fewer features in 1D images, Liao et al. proposed a triple line-scan camera configuration arranged in tandem. By leveraging the acquisition time and imaging positions of a point passing through the fields of view of three line-scan cameras, a bundle adjustment model is built to estimate motion vectors and reduce the impact of motion uncertainty on measurement accuracy. The proposed method reduces the root mean square error from 0.063 mm to 0.053 mm. To enhance compatibility with structured light projection, Ma et al. proposed two system architectures: one uses an area-scan camera to impose constraints among several profiles within its view and refine stitching poses⁶⁶; the other employs a triple line-scan camera array with both co-planar and non-coplanar line-scans to realize motion estimation and stitching accuracy control⁶⁷. The first design minimizes local error accumulation, while the second features a more flexible optical path which can achieve narrow-spaces detection. The two methods are presented in Fig. 14(a,b). Even under significant dynamic disturbances, these methods still achieve a detailed 3D reconstruction accuracy higher than 0.15 mm.

Macroscopic accuracy control

Macroscopic accuracy control plays a crucial role in overall surface shape analysis, defect localization and extension trajectory evaluation. As illustrated in Fig. 15, the requirements are defined by: 1) establishing sufficiently large (decameter to kilometer-scale) or theoretically extensible

global constraints, 2) variable precision levels from millimeters to meters depending on application needs, and 3) the capability to maintain accuracy control during continuous motion.

Although its precision requirements are generally lower than those microscopic-level methods, it remains a critical aspect of quality assurance. Common strategies include methods based on macroscopic positioning and approaches utilizing characteristics with specific interval distributions.

Macroscopic positioning methods often employ global navigation satellite system (GNSS) to track the position of the moving measurement system^{17,68,69}, as is presented in Fig. 16. These technologies are widely deployed, but their accuracy is often limited, typically ranging from the centimeter to meter scale. Meanwhile, reliable localization remains challenging in areas with poor signal coverage such as tunnels¹⁷. Brief interruptions in GNSS signals can be mitigated through multi-sensor fusion technologies, such as integrating GNSS with inertial measurement units (IMUs) or odometry data^{68,70}. Nevertheless, sustained GNSS signal interruptions cause the absolute positioning error of the inertial navigation system to drift quickly (e.g., from <0.1 m to 0.47 m⁷⁰), despite its inherent quality. Some studies have also explored alternative positioning technologies, such as wireless fidelity (Wi-Fi)⁷¹ with an accuracy of a few centimeters. However, the cost of installing and maintaining the equipment for each tunnel is a major issue⁷². In measurement scenarios where the scale of the measured surface is relatively controllable, high-precision positioning instruments such as total stations, laser trackers, and stereo cameras can be employed to correct the macroscopic accuracy of 3D point cloud within their observation range^{73,74}. This kind of method is widely employed in industrial applications, and commercial 3D scanning systems include Hexagon's AS1 and Creaform's MetraSCAN. However, the measurement range of external positioning sensors is limited, rendering some methods inadequate for elongated

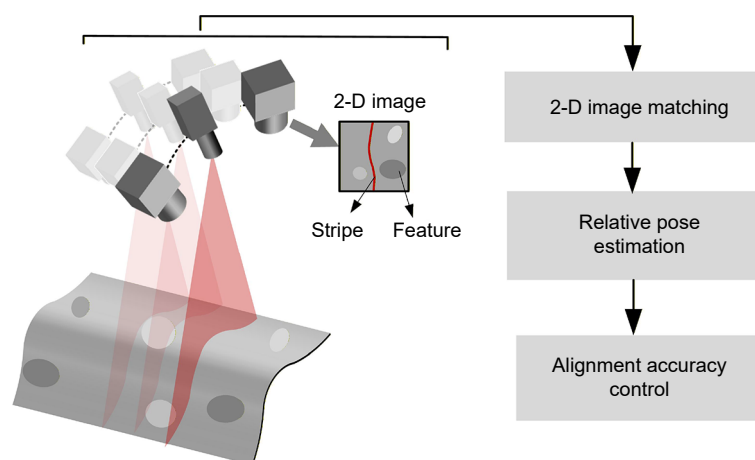


Fig. 13 | Profile point cloud stitching control based on adjacent image matching. Figure reproduced with permission from: ref.⁶⁵, Multidisciplinary Digital Publishing Institute.

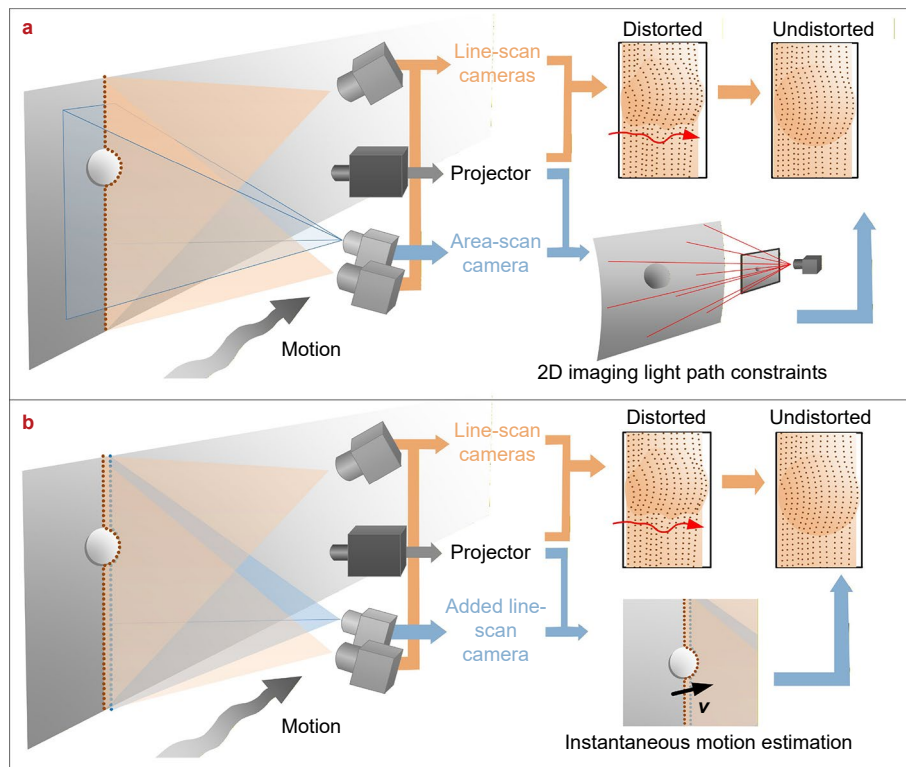


Fig. 14 | Method for microscopic accuracy control oriented toward line-scan vision systems. (a) Using constraints from an area-scan camera. (b) Utilizing constraints from triple line-scan camera array. Figure reproduced with permission from ref. ⁶⁶, Elsevier.

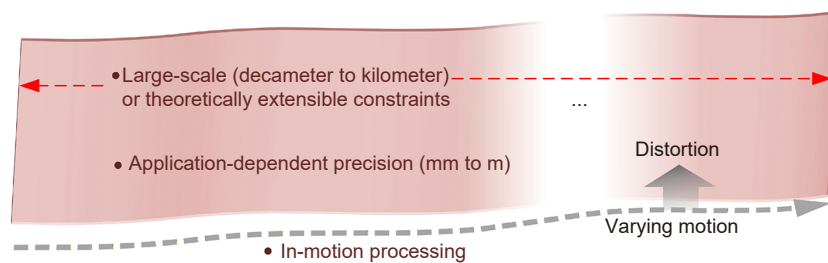


Fig. 15 | Specific requirements for macroscopic accuracy control.

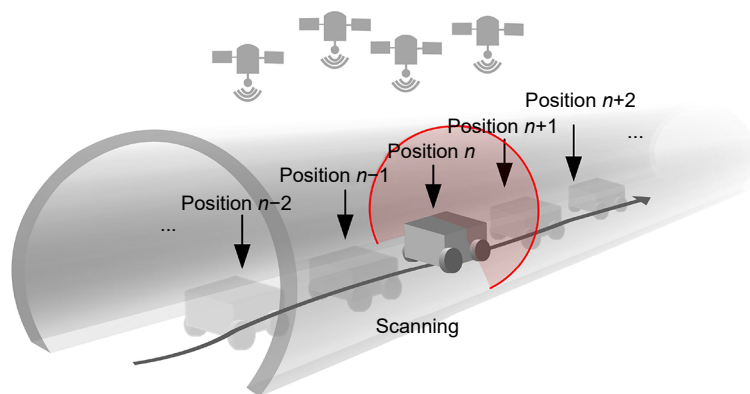


Fig. 16 | GNSS is utilized for macroscopic positioning and large-scale point cloud accuracy control.

spaces with theoretically infinite extension. Consequently, Shi et al. utilized several stereo trackers to supply positioning data for a 3D scanner, thereby ensuring accuracy in the macroscopic expansion of the point clouds⁷⁵. The stereo tracker sequence guarantees effective tracking across long scanning trajectories, enabling accurate integration of all scanner data into a single global coordinate system. Considerable accuracy (about 4 mm) is maintained by this method. Figure 17 illustrates a schematic diagram of the method. However, this type of method employs positioning sensors with limited measurement frequency and non-negligible observation noise⁷⁶, making it difficult to achieve microscopic accuracy control at the same time.

In addition to using positioning sensors, intrinsic features distributed at regular intervals along continuously

extended surfaces can also be utilized. For instance, Liu et al. employed deep learning methods to identify railway fasteners distributed at specific distances, enabling scan trajectory correction and the acquisition of high-precision large-scale point clouds⁷⁷, as shown in Fig. 18(a). Experimental results show that the mileage positioning error is within about 6 cm, which provides accurate mileage results for 3D scanning trajectory calculation. This approach mitigates the error accumulation associated with encoder-based method, as mentioned before. Similarly, studies by Odaka et al. and Cui et al. made use of concrete joints that exist at regular intervals in tunnels^{36,72}, as presented in Fig. 18(b). The method in Odaka's research achieved mean and maximum corrected errors of 0.063 m and 0.125 m. Besides, Odaka also used inherent lighting equipment inside the

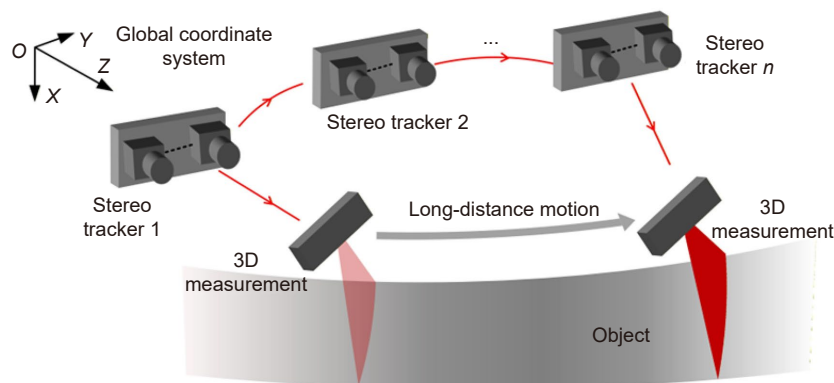


Fig. 17 | Stereo trackers are designed and employed for macroscopic accuracy control.

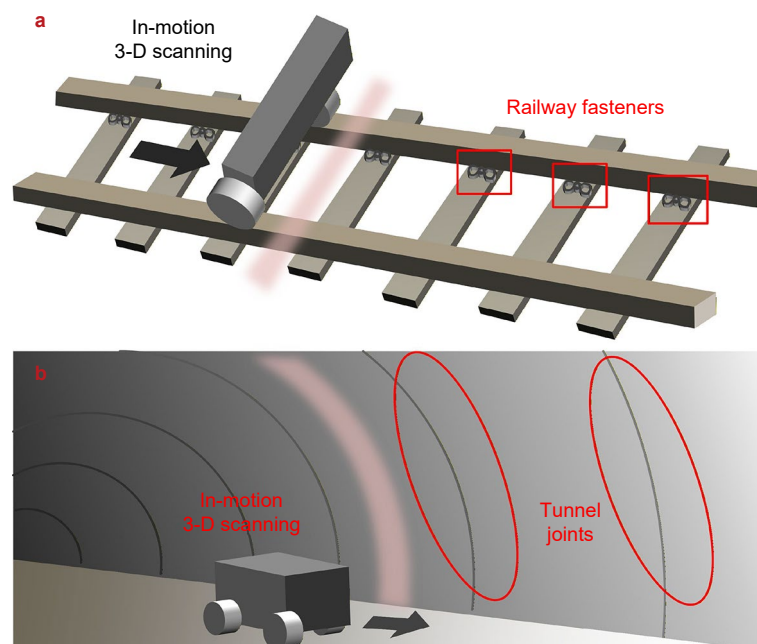


Fig. 18 | Macroscopic accuracy control methods using intrinsic features distributed at regular intervals. (a) According to railway fasteners. (b) According to tunnel joints.

tunnel as landmarks. Some researchers have also utilized detected hydrants and lanes for accuracy control⁷⁸. However, such landmarks serving as control points are replaced every few years and may vary with each periodic inspection. Boavida et al. employed square stickers of a specific size, affixed at predetermined intervals along the tunnel, as critical control points to correct the trajectory during laser scanning in situations where GNSS signals are unavailable¹⁷. Errors are predominantly concentrated in the 1-2 cm range.

Completeness assurance during dynamic scanning

In many in-motion extended-range 3D measurement scenarios, it is often impractical to perform repeated or reverse scans to compensate for local missing point clouds. Typical applications include tunnel scanning during active traffic conditions and real-time workpiece inspection on operating production lines. As a result, for the specific problem of in-motion extended-range measurement, the completeness assurance mandates: 1) avoiding repeated or reverse scans for compensation across the extended range; 2) exhibiting robustness against complex industrial surface properties (e.g., reflectivity and curvature); and 3) acquiring complete 3D data throughout continuous motion. The above requirements regarding completeness assurance is presented in Fig. 19.

Facing complex optical properties

Surfaces with complex optical properties often show signifi-

cant variations in reflectivity. In optical measurement, localized overexposure or underexposure can result in point cloud calculation failures due to image saturation or low signal-to-noise ratio (SNR), thereby compromising the completeness of 3D shape measurement results. This relates to a typical issue known as high dynamic range (HDR) measurement. Moreover, performing such 3D measurements on moving platforms further increases the difficulty of HDR measurement.

For laser scanning systems—ideally suited for in-motion 3D measurements—developing HDR capabilities is key to expanding their use in scenarios with complex optical properties. Niu proposed the deep feature recovery (DFR) strategy to enhance low-light laser stripe images for achieving HDR 3D reconstruction with low cost, high robustness, and eye safety⁷⁹. Figure 20(a) illustrates the procedure of the method. It tackles the challenge of high measurement costs associated with measuring HDR surfaces in laser 3D measurement. Koutecky et al. realized automatic generation of scanning positions based on a computer model of HDR surfaces⁸⁰, as presented in Fig. 20(b). The simulation process is based on a reflectance model proposed by Nayar and simplified by Ellenrieder. This model is suitable for materials that are characterized by the combination of diffuse and specular reflections. Subsequently, the sensor viewpoints are planned to ensure optimal observation of reflective surfaces, followed by generating the shortest path. The observation exposure time for each position is also automatically calculated to optimally adapt to the characteristics of HDR surfaces. Similarly, Yang et al. modeled the specular reflection of reflective surfaces based on the Phong

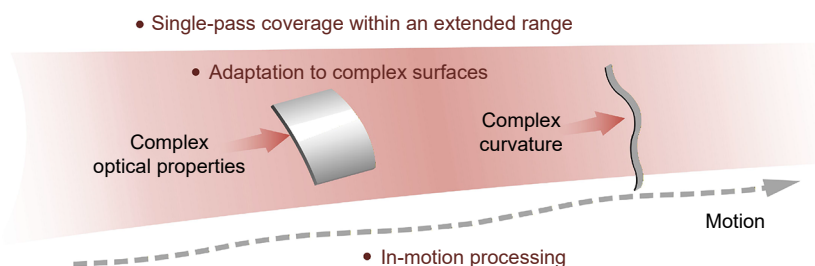


Fig. 19 | Specific requirements for completeness assurance.

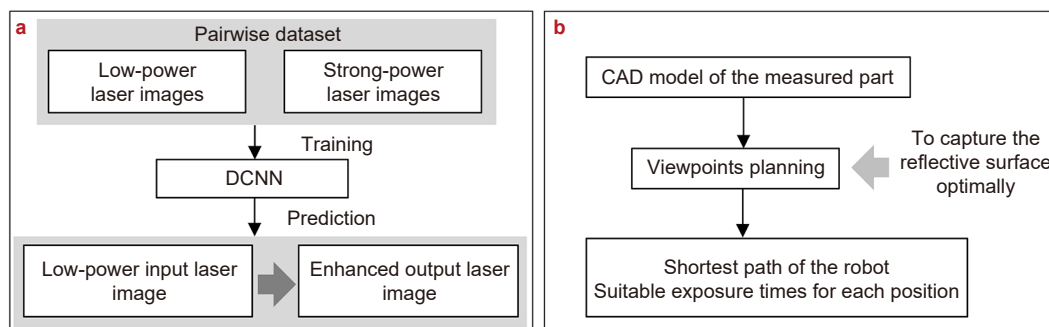


Fig. 20 | HDR measurement based on software algorithms for laser scanning systems. (a) Deep feature recovery strategy to enhance low-light laser stripe images. (b) Automatic generation of scanning positions based on computer models.

reflection model and a photometric response function, and successfully predicted the best view-point from a set of candidate viewpoints for the subsequent measurement⁸¹. In addition to the use of algorithms, hardware-based approaches can also be employed to realize HDR measurement. A widely used method involves employing polarizing filters to eliminate the effects of highlights by limiting the reflected light incident on the image sensor at a certain angle^{82,83}. However, this comes at the expense of reducing the overall captured light intensity, which can result in a low SNR. Differently, Yang proposed an optical imaging system based on a high-resolution liquid crystal on silicon (LCoS) device and an image sensor (CCD or CMOS). The LCoS controls the attenuation ratio at the pixel level based on the irradiance of the incident light, and the image's brightness is adjusted as required⁸⁴. The radiance value of the image is constrained to lie within the dynamic range of the sensor through pixel mapping between the LCoS mask plane and image plane.

In fringe projection systems, the projected structured light is less concentrated in energy compared to laser, making the system more susceptible to reflectivity variations. Extensive research has been conducted by scholars to address this issue, and the proposed methods can be broadly categorized into several categories, including multi-exposure techniques, optimization of exposure time, adjustment of projected pattern intensity, the use of polarizing filters, and multi-color approaches^{85–90}. These methods have achieved remarkable results. Nevertheless, they are primarily designed for conventional static 3D measurement based on area-scan cameras with area structured light. In order to make these methods applicable for in-motion extended-range 3D measurement, a feasible approach involves modifying the method for integration into line-scan camera-based structured light measurement systems. For instance, Ma et al. proposed a HDR measurement method that combines dual RGB line-scan cameras with an RGB projector⁹¹. This system enables synchronous acquisition of surface images with different responses to illumination in continuous motion through high-frequency 1D imaging in three color channels. The method further introduces a gray-white image-based background normalization technique to extend the dynamic range, and employs phase accuracy evaluation metrics to fuse measurement results from different color channels. A schematic of the method is provided in Fig. 21. In recent years, the continuous advancement of deep learning technologies has made it a highly prominent research direction. Investigating neural network techniques to achieve intelligent HDR measurement is significant. Liu's paper reports a new SL-based method to measure parts with highly reflective surfaces from only a single exposure⁹². They designed a skip pyramid context aggregation network (SP-CAN) to enhance the single-exposure images while preserving detailed encoded phase information near edges

and corners during enhancement. It can be foreseen that the application of deep learning in the field of in-motion extended range measurement can play a crucial role in enhancing the efficiency and reliability for HDR surface reconstruction.

Facing complex surface curvatures

Variations in surface curvature can easily lead to blind spots in observation, compromising the completeness of surface 3D shape measurement. A common solution is to increase the number of sensors, obtain the external parameters of each sensor through calibration, and fuse the point cloud measurement results. For example, railway tracks consist of areas with varying curvature characteristics such as the rail waist and rail head⁹³. The integration of multiple measurement systems enables comprehensive observation of railway surfaces. Similar approach is also used in tunnel wall scanning, where multiple cameras jointly capture the large circular profile^{8,94}. The schematic diagram of the aforementioned methods is presented in Fig. 22. The aforementioned CAD-based method can also enhance measurement completeness over complex surface curvatures through a pre-planned viewpoint strategy⁸⁰. However, this method is relatively complex to implement and relies on prior model information.

Apart from adding sensors, the system blind areas can be reduced through a redesigned sensor cooperation strategy. For instance, cameras with different viewpoints exhibit distinct observation ranges, each with certain blind areas. In conventional binocular stereo vision, the final blind areas are the combination of the individual blind zones of both cameras, which adversely affects the acquisition of complete 3D shape. In Lin's method, two area-scan cameras and one projector are treated as independent imaging units. By pairing them in different combinations, three subsystems can be formed⁹⁵. These subsystems are unified within the same coordinate system, and the final measurement result is obtained by merging the point clouds from all three subsystems. As a result, the overall blind zone is no longer the union but rather the intersection of the subsystem blind areas, significantly improving measurement completeness⁹⁶. A schematic of the method is provided in Fig. 23(a). Although this method has not yet been applied to in-motion extended-range 3D measurement scenes, its underlying idea offers valuable insights. For instance, Ma et al. adapted this approach to a line-scan camera system, achieving mutual cancellation of the blind zones between two line-scan cameras⁹⁷. Moreover, the method supports the non-coplanar arrangement of dual line-scan cameras, establishing constraints in motion direction that enables point cloud registration accuracy control during variable motion. Figure 23(b) depicts a schematic illustrating the proposed method.

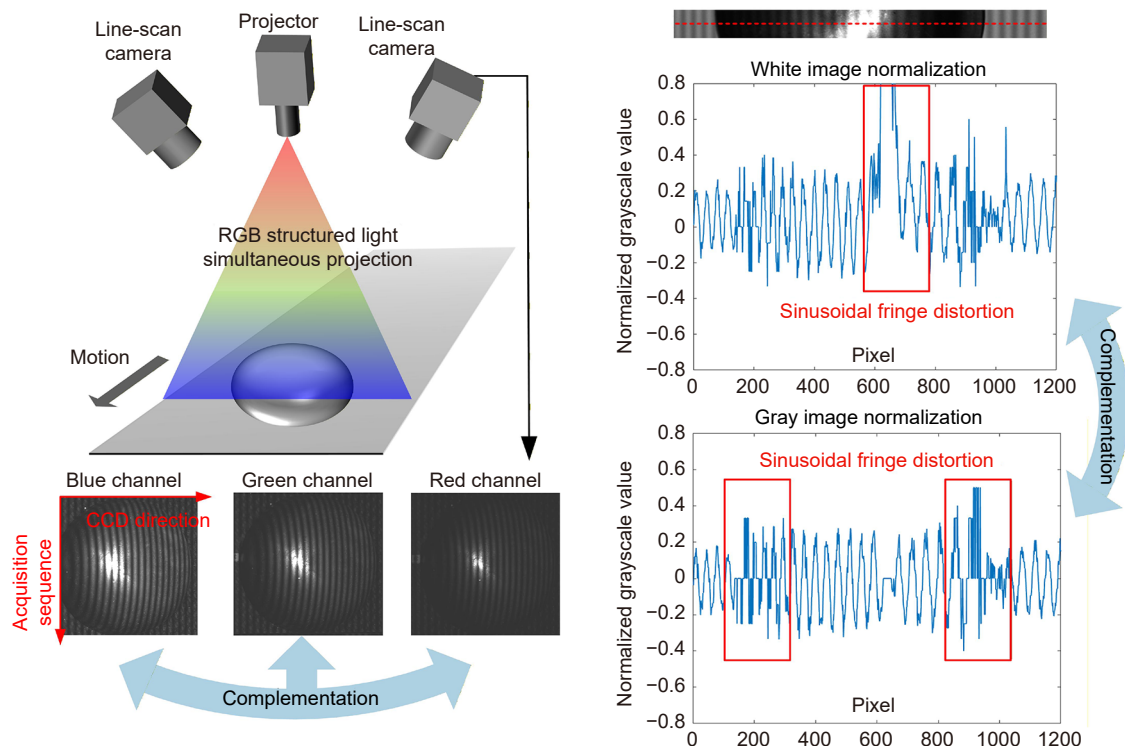


Fig. 21 | In-motion HDR measurement based on RGB fringe projection and gray-white image-based background normalization for line-scan camera system. Figure reproduced with permission from ref.⁹¹, Optica Publishing Group.

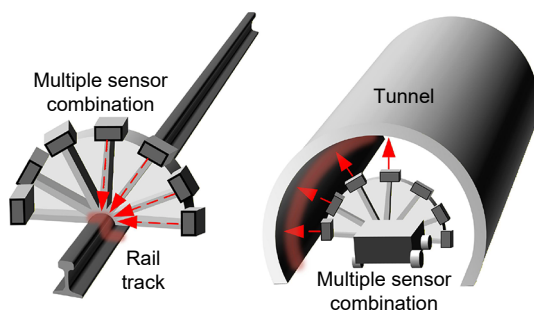


Fig. 22 | Complete 3D measurement through sensor integration and point cloud fusion.

Future development directions

Driven by continuous industrial advancements and the growing demand for surface inspection capabilities, the key future development directions and challenges in extended-range in-motion 3D shape measurement technology include the following.

High speed and high resolution

Achieving high-speed dynamic scanning is critically important in the future. For instance, current train inspection is typically performed either when the train is entering the station at a relatively low speed or by using mobile robots operating at controllable speeds. A critical future objective is to achieve 3D shape measurement while trains are

running at high speeds. With industrial upgrading, the demand for increased production capacity has become increasingly urgent. Production line speeds are increasing accordingly, making high-speed 3D scanning of pipeline components a pivotal goal. Meanwhile, measurement resolution serves as a core indicator, directly influencing the ability to capture and analyse minor defects. Dense point cloud generation based on high-resolution scanning aligns with the growing need for detailed and refined inspection. Simultaneously achieving high speed and high resolution poses substantial challenges, as extremely large volumes of data must be captured and processed in a very short time, exceeding the limits of existing hardware and algorithms. In the future, it will be necessary to systematically address these technical challenges through optimized hardware design for sensors and light sources, advanced software algorithm development, and overall cost control.

Free of trajectory restrictions

In the future, the movement of 3D measurement sensors will no longer be bound by strict trajectory restrictions, offering greater operational freedom and reduced requirements for mobile platforms. This trend is a natural response to the increasing size of industrial components and the growing complexity of inspection environments. To meet these demands, it is essential to further investigate coordinated macro and micro accuracy control methods and explore technical approaches that balance motion

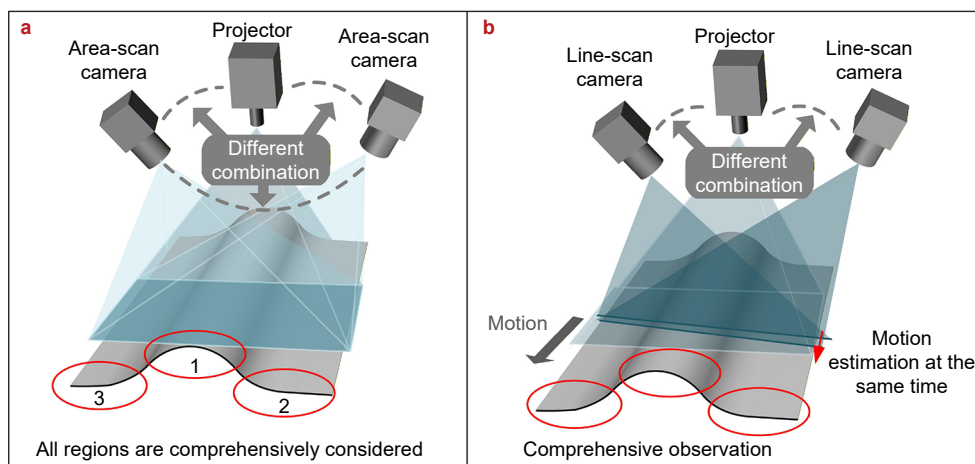


Fig. 23 | Blind area reduction through a redesigned sensor cooperation strategy. (a) Area-scan camera system providing effective reference ideas. (b) Relevant line-scan camera system for in-motion extended-range measurement.

flexibility with accuracy assurance. The ultimate goal is to accomplish high-precision 3D shape measurement without relying on predefined motion trajectories or strict speed control.

Integration with intelligent detection

Defect detection is vital to both national economy and public safety, and there is zero tolerance for potential risks in railway and aircraft systems. Although achieving high-speed, high-resolution, and high-precision acquisition of extended-range 3D shape is highly important, the 3D data must be transformed into evaluation results that can provide practical guidance. Conventional manual analysis is not only inefficient but also particularly inadequate when handling massive high-density point cloud datasets. In the context of rapidly advancing deep learning technologies, the accurate, reliable, and efficient defect identification and quantitative evaluation along with in-motion 3D shape measurement has become increasingly critical, enabling the timely prevention of potential safety hazards.

Establishment of standardized evaluation framework

Given that in-motion extended-range 3D measurement represents a distinct paradigm fundamentally different from convention large-scale 3D metrology, there is an urgent need to develop a corresponding standardized evaluation framework. This framework should systematically define assessment methodologies across multiple dimensions to ensure the reliability and comparability of such dynamic measurement systems. Key components should encompass: standardized protocols for macro-scale geometric accuracy, micro-scale detail fidelity, global positioning precision of features, and 3D shape completeness—particularly over an extended range. Furthermore, performance benchmarks should be established based on critical operational parameters such as extension speed and spatial reso-

lution, enabling objective comparison across different system implementations.

Summary

This paper has presented the state of the art of in-motion extended-range 3D optical measurement for industrial applications. The measurement procedure is explained, and several key challenges within the process are identified. Subsequently, a detailed review is provided on commonly used optical methods for 3D point cloud generation and extension. Methods for microscopic and macroscopic accuracy control during continuous motion are demonstrated, along with strategies for completeness assurance in a single dynamic scan. Perspectives on future development directions and challenges are discussed.

We hope to convey the research status of these technologies to readers and stimulate further in-depth research. For instance, important directions include refining relatively mature methods like laser scanning and area-scan vision for specific industrial scenarios with extended surfaces, as well as advancing promising measurement techniques such as line-scan vision characterized by high frequency and high resolution. Building on existing methods for measurement accuracy control and completeness assurance, we can gradually overcome motion constraints along specific paths or within certain ranges and better adapt to complex environments and diverse surface characteristics, such as those found in industrial manufacturing and in-service equipment maintenance. This will constitute a critical step toward widespread adoption, providing essential support for the ongoing digital and intelligent transformation of industry.

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Author contributions

All authors commented on the manuscript. Luyao Ma wrote the original draft and drew the pictures. Jigui Zhu and Linghui Yang proposed the original idea. Zonghua Zhang supervised the project. Nan Gao, Zhaozong Meng and Yubo Ni reviewed and edited the manuscript.

Competing interests

The authors declare no competing financial interests.



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