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Advancements and Challenges in 3D Scanning: A Comprehensive Review of Engineering Applications

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Abstract

3D scanning has become an essential technology in modern engineering, enabling precise digital replication of physical object across various industries. This paper provides a comprehensive review of 3D scanning applications, highlighting its role in reverse engineering, quality control, additive manufacturing, and healthcare. The study explores different scanning techniques, including structured light scanning, laser triangulation, photogrammetry and coordinate measuring machines (CMMs), emphasizing their strengths and limitations. Additionally, the paper examines the integration of 3D scanning with industry 4.0, advancement in AI-driven scanning, and future technologies trends. While 3D scanning has revolutionized sectors like aerospace, automotive and medicine, challenges such as high costs, data processing complexities, and materials constraints persist. This review aims to provide insights into the evolution, challenges, and prospects of 3D scanning, offering valuable information for researchers and industry professionals.

Keywords: 3D Scanning, Additive Manufacturing, Quality Control, Reverse Engineering, Photogrammetry, Laser Triangulation, Industry 4.0.

Introduction

3D scanning is a rapidly advancing technology that captures the precise dimensions of physical objects in three dimensions (X, Y & Z axes), producing digital replicas well known as Standard Tessellation Language or Stereolithography (STL). These replicas vary in resolution due to factors such as the distance between recorded points at a given scanning range (Chikkangoudar et al., 2020). 3D scanning has been essential for numerous applications, including the scanning of mechanical parts (Afteni et al., 2022), human anatomy such as tissues and organs (Paramasivam et al., 2020), 3D scanning of pre-construction sites and buildings (Sadeghineko et al., 2024). The data collected serves various purposes which includes geometric documentation (Bitharis et al., 2022), inspection(Pathak & Singh, 2017), navigation (Droeschel et al., 2017), visualization (Kot et al., 2016), artifacts preservation (Stoean et al., 2024) and object identification (Verykokou & Ioannidis, 2023). Advanced imaging equipment such as, specialized cameras (Cui &

Stricker, 2011) or laser scanners (Böhler & Marbs, 2005), Coordinate-measuring machines (CMM) (Krawczyk et al., 2015), and commercial Computed Tomography (CT) (Gapinski et al., 2014) scanners to take detailed 3D photographs of the object. By collecting data from multiple angles, 3D scanners create comprehensive digital representations of objects, known as 3D models(Haleem et al., 2022). In industries, this process is often referred to as reverse engineering (RE), where 3D scanning transforms physical models into digital replicas for manufacturing and other applications.

Traditional manufacturing methods often face challenges with complex geometric. However, integrating 3D scanning (reverse engineering) and additive manufacturing (AM) simplifies the production of complex structures. Unlike conventional methods, producing a simple cube requires roughly the same time and effort as creating a complex structure of similar volume. This advantage, often described as "complexity for free," highlights how the shape of a product becomes irrelevant (Wang et al., 2023). With Additive Manufacturing, products can be manufactured directly from 3D CAD models without the need for extensive process planning. For seamless manufacturing, 3D scanners demand high resolution to capture intricate surface details. Both contact and non-contact scanners, such as 3D laser scanners and structured light scanners, offer excellent precision. The accuracy of portable 3D scanners depends on factors like scanning distance and reconstruction quality. Among these, structured light scanners provide superior resolution and accuracy compared to laser scanning systems in reverse engineering (Haleem et al., 2022),(Kanishka & Acherjee, 2023),(Rab et al., 2021).

Reverse engineering is valuable for creating new components when original CAD designs are unavailable. This process begins by generating a CAD model from physical dimensions measured from an existing object. In cases involving complex geometries that are challenging to redraw using CAD software, 3D scanning offers a practical solution (Abdelmomen et al., 2020; R. Gupta and H. Chaudhary, 2017). The synergy between 3D scanning and additive manufacturing has revolutionized industries such as aerospace, automotive and medical field, these technologies now extend beyond prototyping to full-scale production of parts and tools, contributing to sustainability goals by enabling lightweight, cost-effective, and environmentally friendly manufacturing. However, limitations such as material constraints, size restrictions, and the need for post-processing remain challenges (Alami et al., 2023).

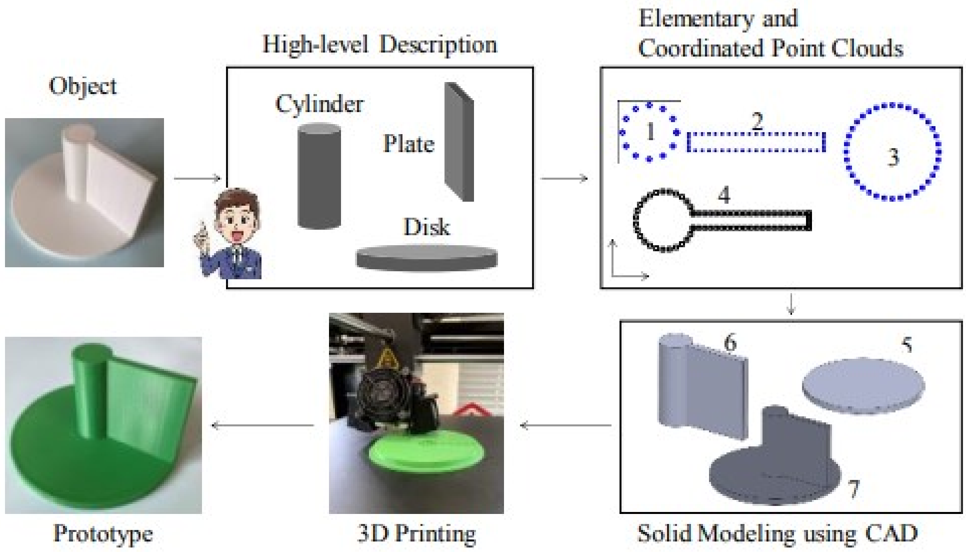
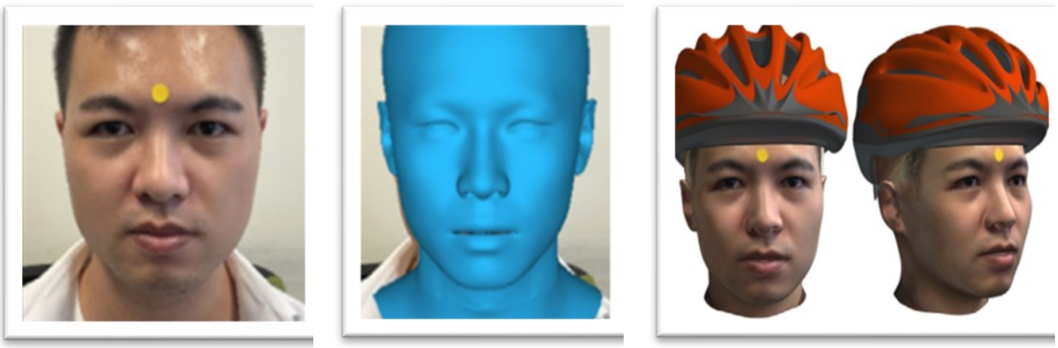


Figure 1: A pictorial representation of reverse engineering method. (Saiga et al., 2023)

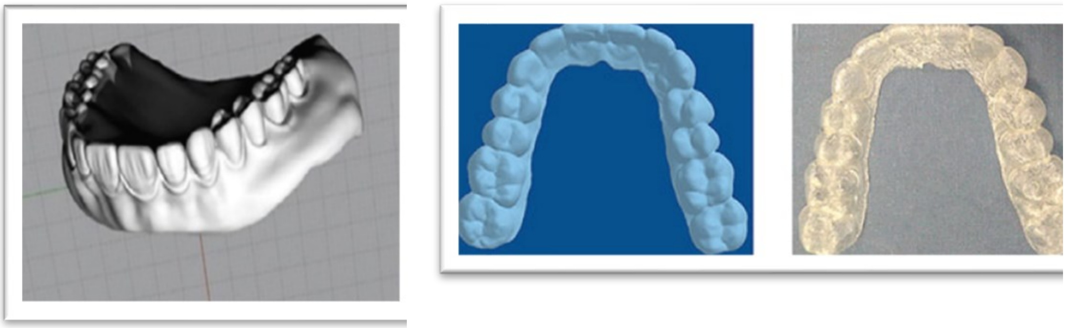
In medical field, it has been observed that each patient has distinct physical characteristics, typically with just minor differences. This uniqueness enables the development of bespoke medicinal aids tailored to each individual. In dentistry, 3D scanning technology has been essential for developing braces, retainers, and mouthguards. It allows for the creation of ideally fitting masks for cosmetic treatments, such as those used to treat burn victims (Javaid et al., 2019)(Alqutaibi et al., 2024). Similarly, bespoke gloves for patients with special hand needs are another significant application (Francesca Sala, Mattia Carminati, Gianluca D'Urso, 2022). Traditional measurement instruments frequently fail to capture the complexities of organic structures, rendering them ineffective for such jobs. In contrast, cone-beam computed tomography (CBCT) has transformed oral and maxillofacial imaging by producing highly accurate three-dimensional representations of complex anatomical structures. This precision enables greater diagnostic accuracy, optimized treatment planning for surgeries and implants, and improved patient outcomes while minimizing radiation exposure through dose-sparing techniques (Ludlow & Ivanovic, 2008). In recent years, 3D scanning has also enabled highly accurate measurements and designs for prosthetic limbs. This precision ensures maximum comfort and mobility by closely matching an individual's body structure, significantly reducing pain and enhancing fit. When combined with 3D printing, the production process becomes faster and more cost-effective compared to traditional methods. This integration empowers doctors and surgeons to make informed decisions, improving surgical outcomes and patient satisfaction (Haleem & Javaid, 2019, 2020; Trybała et al., 2021). 3D scanning technology, widely applied in various healthcare and biomedical sectors, has driven substantial advancements by enabling the rapid development of detailed 3D models that can be shared with medical practitioners to streamline workflows and enhance patient care. Over the past decade, advancements in technology have significantly expanded the applications of 3D scanning, spanning various sectors such as aerospace and automotive. In aerospace engineering, this technology has been employed for geometric assessment and structural integrity analysis of aircraft. To facilitate the studies, a customized toolchain for processing 3D scan data was developed, incorporating geometry extraction, airfoil smoothing, and alignment with aerodynamic models. The results demonstrated the toolchain's effectiveness in accurately reconstructing design geometries, identifying deviations caused by manufacturing or scanning inaccuracies, and enhancing aerodynamic simulations of aerospace components. These findings emphasize the role of 3D scanning in optimizing design validation and performance prediction in the aerospace sector.(Brügge et al., 2023)

The various 3D scanning techniques for data acquisition have been applied to automotive applications, where the performance of two handheld scanners Laser Scanner (ViuScan) and White Light Scanner (GoScan) was compared in the context of reverse engineering (RE). The results indicated that the laser scanner is better suited for tasks requiring high precision, while the white light scanner excels in scenarios demanding speed and ease of use. Each scanner has its own strengths and limitations, making the choice of scanner dependent on the specific application requirements (Ameen et al., 2018). Additionally, 3D scanning technology has been explored for daily quality inspections of automotive door panels, demonstrating a significant reduction in inspection time (by 3.3 hours) and improved data reliability. However, it was found insufficient to entirely replace traditional methods due to challenges in measuring hole diameters and edges. A combined approach, utilizing both 3D scanning and conventional checking fixture methods, was recommended for optimal results (Bin Abdul Razak et al., 2016).



Face Image (a) Reconstructed Head (b) Virtual Helmet (c)

Figure 2: Application scenarios of 3D head reconstruction through 3D scanning: consisting of (a and b) head shape reconstruction and (c) helmet template deformation.(Zhang et al., 2022)



3D illustration of denture file from a design software (Khorsandi et al., 2021)

3D CAD drawing of an orthodontic aligner (left panel) and the photograph of the corresponding aligner fabricated by SLA (right panel).(Makvandi et al., 2017)

Figure 3: 3D illustration of a denture file from design software, alongside a 3D CAD drawing of an orthodontic aligner and the photograph of the corresponding aligner fabricated using SLA.

3D scanning is an essential tool for ensuring quality control after manufacturing and for verifying the precision of both traditionally and additive manufactured parts. With numerous portable 3D scanners available, each offering distinct features, choosing the right system that meets both functional needs and budget constraints can be challenging. This technology supports various applications, including replication, restoration, reverse engineering, and dimensional metrology. When integrated with 3D printing, 3D scanning can streamline the design and production of components, significantly boosting efficiency. However, some scanners generate oversized mesh files that can impede further processing steps. Advanced scanning software helps address these challenges by repairing small defects and optimizing the scanned data for easier CAD integration. Today, 3D scanners are widely used by product manufacturers and professionals of various fields to quickly create accurate digital replicas. These models can be derived either by reverse-engineering existing designs or by capturing complex geometries (Lee et al., 2021; Pontevedra, 2019). Section **Error! Bookmark not defined.**.0 presents a general overview, introduction, and a brief review of relevant literature. Section 0 below explores the different classifications of 3D scanning. Section 0 explains the working principles of 3D scanners. The challenges and limitations associated with 3D scanning are examined in Section 0. Section 0 outlines future prospects and technological advancements in the field. Lastly, Section 0 summarizes the key point and concludes the paper.

Classifications of 3D Scanning

Advancements in technology have greatly shaped the evolution of 3D scanning methods, making them increasingly sophisticated and accurate in addressing design challenges. The following are some of the most commonly used 3D scanning processes across various application areas.

a. Structured light 3D Scanning
b. LASER triangulation 3D scanning
c. Structured light 3D Scanning Photogrammetry
d. Coordinate measuring machine (CMM) (Haleem et al., 2022)

Structured Light 3D Scanning:
A structured light 3D scanning system is a non-contact technology comprising a projector and at least one camera, data acquisition and analysis are managed by dedicated software running on personal computers, which serve as integral components of the system. These scanners work by projecting a known light pattern such as stripes or dots, typically regular and periodic onto the object. The projected pattern is then captured by one or more cameras, and the software processes the data to reconstruct the object's 3D geometry using triangulation or various projection geometries (Rieke-zapp & Royo, n.d.). Structured light 3D scanners operate by projecting a pattern of light onto a subject and detecting the deformation of the pattern caused by the subject's surface. These patterns can be either one-dimensional, such as a line, or two-dimensional, such as a grid or striped lines. For one-dimensional patterns, the line is typically projected onto the subject using an LCD projector or a sweeping laser, while two-dimensional patterns are more complex. A camera captures the deformation of the projected pattern, and sophisticated algorithms are then applied to calculate the distance at each point within the pattern. The complexity of this process arises from challenges such as ambiguity in the captured data. The primary advantage of structured light 3D scanners lies in their speed. Unlike traditional methods that scan one point at a time, structured light scanners can simultaneously capture multiple points or even the entire field of view. This capability significantly reduces or eliminates distortions caused by motion, making them highly efficient and effective for 3D scanning applications.(Georgopoulos et al., 2010)

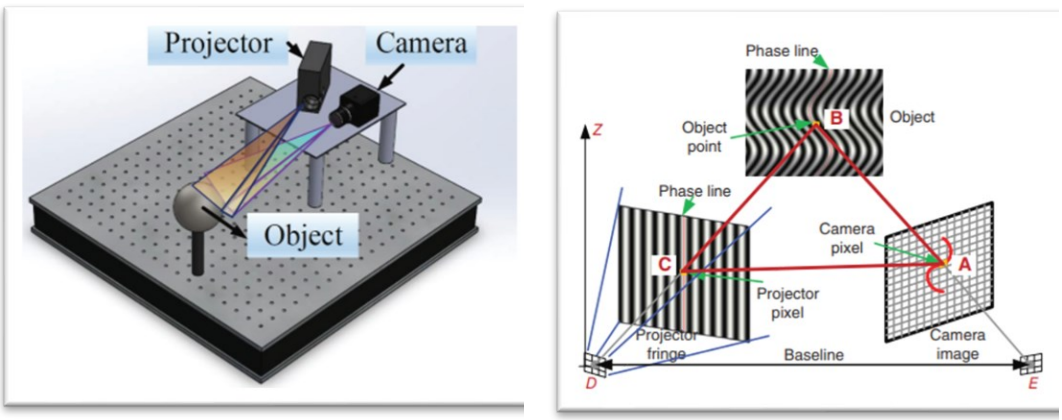


Figure 4: Illustration of a structured light system containing one projector, one camera, and an object to be captured (Left). (b) Schematic diagram of a 3D structured light imaging system using fringe projection (Right) (With & Dfp, 2016).

LASER Triangulation 3D Scanning:

Laser triangulation measurement is a laser-based non-contact optical displacement detection method. The optical signal with collected displacement information is first converted into electrical signals. The measured surface displacement is obtained by computer processing to recognize these signals. There are two major types of laser triangulation method: Direct type and Oblique type. The direct type is suitable for measuring surfaces with good scattering, while the oblique type is appropriate for parts with smooth surfaces. Therefore, the laser triangulation on-machine measurement (LTOMM) method can be fine-tuned according to the machined surface roughness to optimize the measurement reliability.

From the triangle similarity principle, the surface displacement can be obtained as:

$$ya = ax\sin\beta / b\sin\alpha + x\sin(\alpha + \beta) \text{ ----- (1)}$$

$$yb = ax\sin\alpha / \sin\beta\, b + x\cos\beta \text{ ----- (2)}$$

where y is the height of H_1 relative to the reference plane, x is the image shift between points M_1 and M_0, a is the imaging object distance at point H_0, and b is the image distance at point H_1, α and β are the angle parameters of the measured sensor. Most commercial laser sensors have integrated calculation functions that can directly output displacement values, thus facilitating the acquisition of 3D information on complex surface profiles. Some are even equipped with an in-built filtering algorithm to further improve measurement accuracy (Ding et al., 2023).

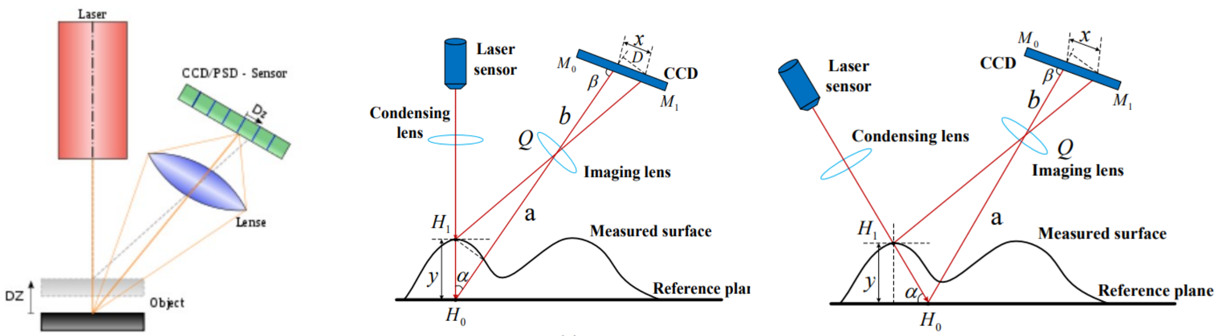


Figure 5: Basic Laser Triangulation Method; Direct Type Triangulation Method; Oblique Type Triangulation Method (Ding et al., 2023)

Structured Light 3D Scanning Photogrammetry:

Digital photogrammetry is a non-contact measurement technique that captures a series of images using imaging sensors such as charge-coupled devices (CCDs), complementary metal-oxide semiconductors (CMOS), or infrared cameras. These images are analysed to determine coordinates, identify patterns and features, or detect object boundaries. By leveraging advanced imaging sensors, photogrammetry enables the extraction of valuable data from photographs, effectively turning a standard camera into a precise measurement tool. This method can accurately determine the shape and position of objects by deriving 3D information from 2D images. When paired with high-quality cameras, robust software, and proper lighting, photogrammetry has consistently demonstrated exceptional accuracy, making it a reliable choice for a variety of applications (Freeman Gebler et al., 2021). Photogrammetry initially found its primary use in aerial and terrestrial applications, driven largely by the demands of military reconnaissance. However, advancements in digital camera technology and the availability of affordable, high-resolution cameras have significantly broadened its scope. Today, photogrammetry is widely applied in various scientific disciplines, including civil and mechanical engineering. Over time, researchers have introduced terms such as close-range photogrammetry, videogrammetry, dynamic photogrammetry, computer vision, machine vision, and robot vision to describe this versatile measurement technique and its diverse applications.

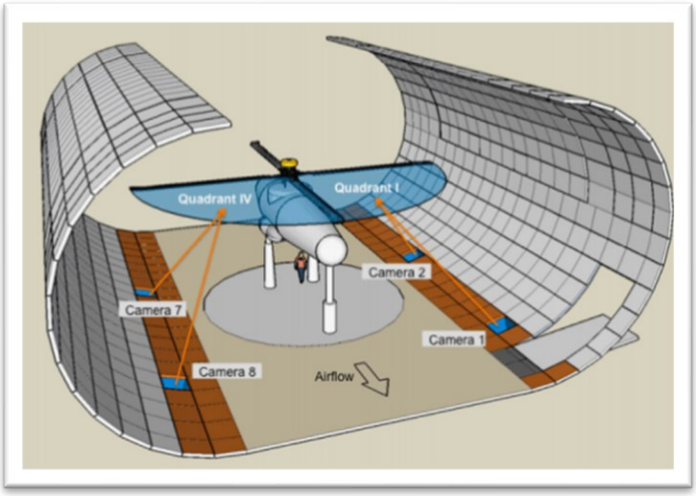


Figure 6: A diagram depicting the photogrammetry setup for measuring a full-scale helicopter rotor system, showcasing the arrangement of four cameras and the triangulation method employed to obtain accurate measurements. (Olson et al., 2010)

Coordinate Measuring Machine (CMM) (3D Scanning):

Digital photogrammetry is a non-contacting measurement approach that uses a series of images recorded with Coordinate Measuring Machines (CMMs) are widely used for 3D inspection of physical components in manufacturing industries. These mechanical systems operate by moving a measuring probe to determine the coordinates of points on the surface of a workpiece. CMMs consist of four key components: the main structure, probing system, control or computing system, and measurement software. Their applications span a broad range of industries, from large-scale sectors like shipbuilding and aerospace to precision-dependent fields such as semiconductor manufacturing. CMMs have significantly transformed quality assurance processes in industries like aerospace, automotive, medical devices, mold and die production, and shipbuilding.

In addition to delivering high accuracy and precision, CMMs offer enhanced convenience, simplicity, and operational speed, making them suitable for measuring a wide variety of products. They also enable advanced capabilities such as automated measurements, graphical result visualization, and seamless integration with computer-aided design (CAD) and computer-aided manufacturing (CAM) systems, ensuring a more efficient and reliable measurement process (Amiri, 2016).

Generic Working Steps of 3D Scanners

3D scanners offer exceptional accuracy, driving significant growth predictions for the reverse engineering industry. A 3D scan captures a detailed representation of a portion of an object's surface, while a 3D model comprises multiple 3D scans. Unlike 2D photographs, which are made up of pixels, 3D scans use triangles or polygons to form a versatile mesh that precisely replicates an object's geometry. These scanners are utilized across various industries, including manufacturing and healthcare, proving invaluable for tasks such as heavy machinery analysis, quality control of mechanical parts, custom prosthetic devices, visual effects in films, and character design for video games (Haleem & Javaid, 2019)(Ling, 2021)(Sepasgozar et al., 2020).

Connectivity of devices: The initial step involves assembling all components of the 3D scanner, attaching the appropriate camera and projector lens combination, positioning the object to be scanned at the focal point of the rotary table, and powering on the device. A blue light indicates successful connections; if the light does not appear, the connections and power supply should be rechecked. Next, the project details are uploaded into the scanning software, which is configured based on the selected lens, rotary table, calibration plate, and other necessary parameters (Berglund et al., 2015).

Configuration and data collection: The next stage is to set up the project and program the rotary table to revolve the appropriate number of times based on the item's size, form, and geometry. The object must be centred on the rotary table and in the scanner's field of view. Key parameters include the quality level (high, medium, or low) and camera resolution (high, medium, or low). To avoid measurement mistakes, validate the sensor temperature before scanning, ensuring it is around room temperature (28 °C and 42 °C). Additionally, the light intensity on the object's surface should be adjusted according to its surface properties. These characteristics have a direct influence on the data collection procedure and the accuracy of the results. Once all parameters are correctly configured and the scanner's temperature is within the acceptable range, scanning can continue. During this operation, the projector shines blue light beams at the object, and the camera captures the reflected beams at its focal point. The software then processes the reflected data to produce precise measurements (Sitnik et al., 2010).

Data optimization: After completing the second rotation, the first and second measurements must be aligned to ensure consistency before proceeding with additional measurements. This initial alignment serves as a baseline to evaluate the precision and accuracy of the alignment process. Once the initial alignment is confirmed, the software automatically aligns all subsequent measurements, streamlining the data collection process. Measurements are carried out sequentially, and upon completion of the final scan, extraneous or irrelevant data collected during the process is identified and removed. The acquired data then undergoes post-processing to enhance its quality and correct any errors. This involves creating a mesh by generating a grid from the data, followed by the removal of holes and any other undesirable artifacts within the mesh. The refined dataset is then saved in various formats, making it compatible with other software tools for further applications. Post-processing is a critical phase that requires meticulous attention to detail to ensure the final dataset is accurate and usable. 3D scanning finds application across diverse fields such as education, research, medicine, design, manufacturing, and engineering. This technology enables significant advancements, particularly in the customized design of products tailored to specific requirements, driving innovation and precision in multiple industries

Challenges and Limitations of 3D Scanning

Despite its numerous advantages, 3D scanning technology faces several challenges that limit its full-scale adoption across industries. These challenges include accuracy limitations, high costs, data processing complexities, and scalability issues.

Accuracy and Resolution Limitations

The accuracy of different 3D scanning techniques varies depending on several factors, including lighting conditions, object reflectivity, scanning distance, and environmental interference. Structured light scanning is highly precise for capturing small objects but encounters difficulties when measuring larger surfaces. Laser scanning, commonly used in industrial applications, delivers reliable results; however, it struggles with highly reflective or transparent surfaces, often requiring special coatings to improve accuracy. Photogrammetry, which relies on high-resolution cameras, can produce detailed scans but is particularly sensitive to motion and lighting variations, potentially leading to errors.

High Cost of 3D Scanning Systems

Advanced 3D scanners and software come with high costs, making them less accessible to small and medium enterprises (SMEs). Industrial-grade laser scanners require a substantial investment, often costing thousands of dollars. Additionally, post-processing software and data optimization tools come with expensive licensing fees, further increasing the overall expense. Moreover, the need for specialized training to enable operators to efficiently use and interpret scan data adds to the financial burden, making widespread adoption challenging for smaller businesses.

Time-Consuming Data Processing and Post-Processing

Although 3D scanning enables the rapid capture of object geometry, the post-processing phase remains time-consuming. Large scan files demand significant computing power for efficient processing. Additionally, tasks such as noise filtering, mesh optimization, and CAD conversion can be complex, requiring skilled expertise. Furthermore, data alignment challenges may arise when merging multiple scans into a single, cohesive 3D model, adding to the overall processing difficulty.

Surface and Material Challenges

3D scanners face challenges when dealing with specific material properties, which can affect scan quality. Highly reflective, transparent, or dark surfaces often introduce errors in the captured data. Additionally, objects with intricate details or deep recesses may require multiple scans to achieve complete and accurate results. Environmental factors such as dust, vibrations, or humidity can further interfere with scan precision, making the process more complex and demanding.

Scalability and Large Object Scanning Challenges

Although 3D scanning is highly effective for small- to medium-sized components, scaling up to larger structures such as buildings, bridges, and aircraft presents significant challenges. The limited field of view (FOV) in most 3D scanners necessitates multiple scans, which must be merged, adding to processing complexity. Handheld scanners can further introduce errors due to operator movement, potentially affecting measurement accuracy. While terrestrial laser scanners (TLS) and LiDAR are better suited for large-scale applications, their high cost makes them less accessible for many users.

Future Prospects and Technological Advancements

With ongoing research and technological advancements, 3D scanning is evolving rapidly to address its current challenges. The following emerging trends are expected to enhance precision, speed, and application range across various industries.

AI-Driven 3D Scanning and Automation

Artificial intelligence (AI) and machine learning (ML) are increasingly being integrated into 3D scanning systems to enhance automation in data processing, error detection, and scan refinement. AI-powered real-time optimization can automatically correct noise, misalignment, and missing data, improving overall scan quality. Deep learning algorithms are being trained to enhance accuracy, particularly in applications such as medical imaging and industrial quality control. Additionally, AI-driven automated defect detection is revolutionizing reverse engineering and quality assurance processes, making them more efficient and reliable.

Advancements in Portable and Handheld 3D Scanners

The latest advancements in handheld and mobile 3D scanners are making the technology more accessible, user-friendly, and cost-effective. Wireless and smartphone-integrated scanners are being developed to enable real-time scanning, enhancing convenience and portability. Hybrid handheld scanners that combine structured light and laser scanning techniques are improving scanning flexibility for various applications. Additionally, the emergence of more affordable, compact 3D scanners is bringing high-resolution scanning within reach for small businesses and hobbyists, expanding the technology's adoption across different industries.

Faster and More Efficient Scanning Technologies

Future advancements in 3D scanning technology focus on increasing scanning speed and minimizing data processing times. High-speed LiDAR and ultrafast structured light systems are significantly enhancing scanning rates, making the process more efficient. The integration of cloud computing enables remote processing of large 3D scans, reducing reliance on high-end local hardware. Additionally, real-time 3D scanning and digital twin technology are set to revolutionize industrial inspection and monitoring, streamlining workflows and improving overall efficiency.

Hybrid 3D Scanning and Multi-Sensor Fusion

The integration of multiple scanning technologies is expected to enhance accuracy and adaptability across various applications. Hybrid scanners that combine LiDAR and photogrammetry provide superior precision, particularly for large-scale projects. Multi-modal scanning systems, which incorporate X-ray CT scanning, laser scanning, and structured light scanning, enable more comprehensive internal and external analyses. Additionally, drones equipped with 3D scanning sensors are expanding the technology's applications in construction, mining, and infrastructure assessment, offering greater flexibility and efficiency in large-area scanning.

Industry 4.0 and Digital Twin Integration

3D scanning is a crucial component of Industry 4.0, enabling the creation of real-time digital twins for predictive maintenance, simulation, and process optimization. Manufacturing plants are integrating 3D scanning with IoT sensors to monitor machinery wear and tear, ensuring proactive maintenance. Digital twins allow companies to simulate real-world scenarios, leading to cost reductions and increased productivity. Additionally, the development of robotic 3D scanning systems is paving the way for fully autonomous quality control and inspection, further enhancing efficiency and accuracy in industrial applications.

Conclusion

The adoption of 3D scanning has revolutionized engineering, manufacturing, and healthcare by enabling precise digital replication of physical objects. Its integration with reverse engineering, additive manufacturing, and quality control has significantly enhanced efficiency and accuracy across multiple sectors. While challenges such as high costs, material limitations, and complex post-processing remain, continuous advancements in AI, multi-sensor scanning, and automation are driving the technology forward. The development of cost-effective, high-speed, and portable 3D scanners is expanding accessibility, making the technology more viable for industries ranging from automotive and aerospace to medical and consumer electronics. As Industry 4.0 and digital twin technologies gain momentum, 3D scanning will play an increasingly critical role in smart manufacturing, predictive maintenance, and real-time process optimization. The continued evolution of AI-powered automation, hybrid scanning systems, and cloud-based data processing will further enhance both the accuracy and efficiency of 3D scanning applications.

In conclusion, 3D scanning is poised to become an indispensable tool in engineering and industrial innovation, seamlessly bridging the gap between physical and digital design processes. As technological advancements continue to address existing limitations, its impact on digital manufacturing and product development will only grow stronger.

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