УДК.621.01

RESEARCH ON 3D MEASUREMENT TECHNOLOGY BASED ON MACHINE VISION

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Measurement is an important means for humans to understand and transform the world, and it is the technological foundation for breaking through the forefront of science and solving major problems in economic and social development. The three-dimensional measurement system serves primary national needs, leads national economic development, and ensures national defense security. With the arrival of a new industrial revolution, major industrial countries worldwide have begun to accelerate the strategic deployment of intelligent manufacturing. As an essential component of the construction of smart factories and lighthouse factories, the 3D measurement system will play a vital role in deepening the implementation of the manufacturing power strategy and promoting the high-end, intelligent, and green manufacturing process. In recent years, optical 3D measurement technology represented by surface structured light has developed rapidly and has been widely applied in multiple material processing fields such as forging, casting, and sheet metal. To analyze the manufacturing accuracy of complex parts using surface structured light 3D measurement technology, it is necessary to first scan and reconstruct the overall 3D surface of the part. The reconstructed 3D point cloud data of the part surface should be roughly and precisely matched with the design model. Finally, based on this, data comparison and accuracy analysis should be carried out according to the actual detection requirements of different types of parts. In this process, the accuracy of 3D reconstruction of complex parts and the alignment accuracy between the reconstruction results and the design model directly determine the reliability and accuracy of the final part manufacturing and machining accuracy analysis. This article uses cases to illustrate the application of machine vision in 3D online measurement. The application of three-dimensional measurement technology in online quality inspection and grinding of blades can not only improve the measurement accuracy of online quality inspection of blades but also maintain the relative stability of robot grinding force and improve the grinding effect in robot grinding of aircraft engine blades. Applied to online quality inspection of train wheel hubs, three-dimensional measurement of train wheel adapters and high-speed train wheel size online inspection has been achieved.

Key words: *digital twin, machine vision, 3D scanning and reconstruction, 3D point cloud registration.*

DOI https://doi.org/10.32782/msnau.2023.4.1

Introduction

Machine Vision is a comprehensive science that is based on a series of geometric optics, classical mathematical algorithms, and integrates modern anatomy, neurophysiology, computer technology, statistics, operations research, graph theory, signal analysis and processing, and other disciplines. It is an important branch of artificial intelligence. With the rapid development of computer vision technology and optoelectronic technology, a new detection technology has emerged – computer vision detection technology (Liming Xue et al., 2023; Yajie Sun et al., 2023; Ahmad Mohamad Mezher et al., 2023; Nazanin Safavian et al., 2023; Elmira Faraji Zonouz et al., 2023). It is a detection method that uses images as a means or carrier for detecting and transmitting information when detecting the target being measured, with the aim of extracting useful signals from the image. It is a modern detection technology based on modern optics, integrating science and technology such as optoelectronics, computer imaging, information processing, and computer vision. Due to its intelligence, digitization, miniaturization, networking, and multifunctionality, as well as its ability to perform online detection, real-time analysis, and real-time control, it has received widespread attention and application in military, industrial, commercial, medical and other fields (Elmira Faraji Zonouz et al., 2023; Kui Luo et al., 2023; Mengran Fang et al., 2023; André Luiz Buarque Vieira e Silva et al., 2023; João Peixoto et al., 2023; Obinna Nwosu et al., 2023; Wu Xiaoqiang et al., 2023; Huang Ziliang, 2023; Wei Yi, 2023; Design…, 2023; Yang Jiahe, 2023; Li Xianzheng et al., 2023; Wu Shaoji & Hu Yike, 2023; Wu Xiaoqiang & Zeng Chaoyang, 2023; Cai Yunbin, 2023).

3D measurement is one of the most important fields among the numerous applications of computer vision. In the past few decades, the rapid development of visual technology has made 3D visual inspection an important component of many automated production systems. Unlike visual pattern recognition and understanding in computer vision research, visual inspection technology is an important means of quality inspection, quantitative inspection, and non-contact measurement. Three-dimensional measurement has many applications in industrial manufacturing, which can be divided into dimension measurement, surface measurement, and coordinate measurement according to primary functions. The current mainstream industrial 3D measurement methods include laser trackers, laser triangulation, photogrammetric systems, structured light, time-of-flight technology, and so on. 3D measurement includes the main processes of data acquisition, data processing, measurement analysis, etc.

Key Technologies of 3D Measurement System

Currently, the commonly used methods for detecting complex parts mainly include specialized fixture inspection, Coordinate Measuring Machine (CMM) measurement, and Photogrammetry. However, these methods can only see the dimensions of the limited positions of the parts. They need help to complete the three-dimensional measurement and accuracy analysis of the overall shape of the parts, making it difficult to provide complete and comprehensive data support for forming process optimization (Li Y & Gu P., 2004). To obtain three-dimensional data of the overall surface shape of parts, optical three-dimensional measurement technology represented by surface structured light three-dimensional measurement technology has developed rapidly in recent years. It has been widely used in multiple material processing fields, such as forging, casting, and sheet metal, achieving good application results (Su et al., 2009; Zhong et al, 2015; Han et al, 2018; He et al, 2018; Cheng et al., 2019).

To analyze the manufacturing accuracy of complex parts using surface structured light 3D measurement technology, it is necessary first to scan and reconstruct the overall 3D surface of the part. The part surface's reconstructed 3D point cloud data should be roughly and precisely matched with the design model. Finally, based on this, data comparison and accuracy analysis should be carried out according to the detection requirements of different types of parts. In this process, the accuracy of the 3D reconstruction of complex parts and the alignment accuracy between the reconstruction results and the design model directly determine the reliability and accuracy of the final part manufacturing and machining accuracy analysis.

3D scanning and reconstruction technology

The 3D scanning and reconstruction technology is affected by the occlusion of the tested part itself and the limitations of the measurement range. A single measurement can only obtain local 3D point cloud data on the part's surface (Zhang, 2010; Li et al., 2013; Zuo et al., 2018). To get complete 3D data of the part surface, it is necessary to constantly change the spatial pose of the measuring equipment during the measurement process, measure the part from different perspectives, and register the local 3D data obtained from different viewpoints into a unified coordinate system (Levoy et al., 2000). To address this issue, the ATOS equipment from German company Gom (GOM Inspect…, 2019) and the HandyScan equipment from Canadian company Creaform (HandySCAN… 2019) use an external positioning-assisted approach to recover the spatial pose of the measured viewpoint. Method 1: The solution of the measurement viewpoint pose is completed by pasting marker points on the surface of the tested part and extracting and matching the features of the marker points(Ouellet&Hébert1, 2008). Method 2: Fix the measuring equipment on a mechanical device (such as a robotic arm) and calculate the measuring equipment's spatial pose by obtaining the automatic device's internal positioning coordinates (Han et al., 2018). Method 3: Uses photogrammetric methods to visually track the measuring equipment from the outside (Cuypers et al., 2009) and calculate the spatial pose of the measuring equipment. These methods have the advantage of high positioning accuracy. Still, the dependence on external positioning assistance affects measurement efficiency and the flexibility of measurement equipment, limiting the application scenarios of structured light 3D measurement technology. As shown in Figure 1.

3D point cloud registration technology

Industrial part models are usually designed in Computer-Aided Design (CAD) software, so they are located in the design coordinate system. The measured part surface point cloud data obtained by scanning with structured light 3D measurement equipment is located in the measurement coordinate system. The difference between these two coordinate systems is usually significant, resulting in a significant initial position deviation between the design data model and the point cloud data when placed in the same coordinate system. Therefore, it is necessary to find a suitable rigid transformation matrix to register the point cloud data and the design data model together. This process is known as point cloud coarse registration (Gelfand et al., 2005; Aiger et al., 2008; Zhou et al., 2016; Rusu, 2009). After obtaining the overall 3D point cloud data of the tested part surface, it is necessary to coordinate/align the measured point cloud data with the design model before proceeding with subsequent key dimension fitting, overall accuracy analysis, and part quality evaluation operations.

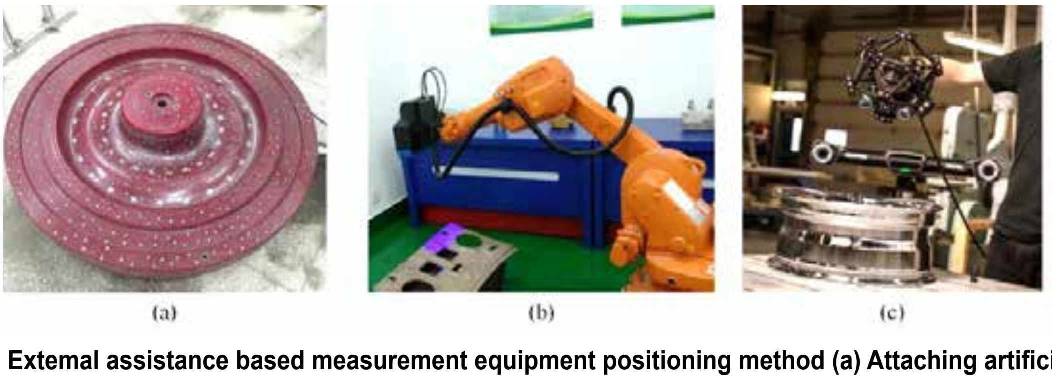

Fig. 1. Extemal assistance based measurement equipment positioning method (a) Attaching artificial marks (b) Mechanical control positioning (c) Visual tracking positioning [31]

For traditional workpieces with simple shapes, coordinate alignment between measurement data and design models can be achieved through the 3-2-1 reference method. However, the overall shape is more complex for complex parts because they are usually composed of multiple free-form surfaces. Therefore, more accurate registration of measurement data and design models is achieved through geometric shape registration.

Because the coarse registration results of point clouds are obtained by registering a sparse set of corresponding points together, and each set of feature corresponding points cannot accurately correspond to the same spatial position, the accuracy of the coarse registration results will not be optimal. Usually, more precise geometric shape registration is required based on this, accurately aligning the measurement data with the design model. As shown in Figure 2.

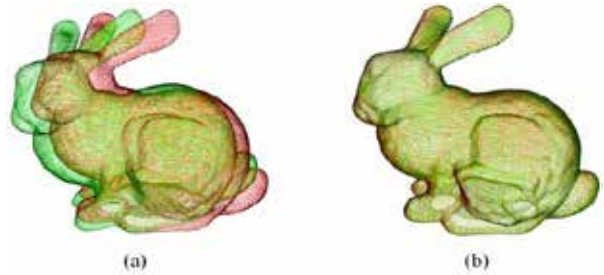

Fig. 2. Point cloud fine registration (a) initial position (b) fine registration result. The point cloud data comes from the Stanford University Graphics Laboratory (Curless B & Levoy M., 1996; Chen Xu, 2019)

Cases

Online quality inspection and grinding of blades

In article (Ghorbani et al., 2019) characterized the difference between local measurement scan data and the standard model by combining the average curvature Hausdorff distance and the average Euclidean Hausdorff distance, accurately separating unreliable damaged area scan data points of blades and improving measurement accuracy. In article (Li et al., 2016) applied three-dimensional measurement technology in robot grinding of aircraft engine blades. They introduced the weight function of stable grinding allowance into the measurement matching system, defining an optimization function based on variance minimization. At the same time, the problem of incorrect matching caused by missing points or uneven density data points in 3D scanning data was solved by balancing the matching weights of all measurement points. Finally, the final measurement point cloud registration parameters were obtained through iterative optimization algorithms. This method avoids data-matching errors caused by uneven scanning data points. It considers different machining allowance requirements for the concave and convex surfaces of the blade, making the three-dimensional measurement results beneficial for maintaining the relative stability of the robot's grinding force and improving the grinding effect. As shown in Figure 3 (b).

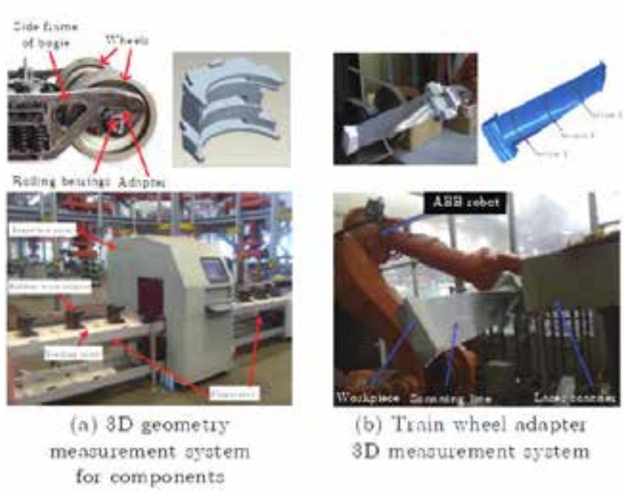

Fig. 3. 3D measurement system for complex structural components [43]

Online quality inspection of train wheel hubs

In article (Zhong et al., 2015) studied the measurement scanning mechanism to solve the problems of surface reflectivity changes and vibration during the scanning process, improve the quality of point cloud data generation in 3D scanning, and achieve 3D measurement of train hub adapters. As shown in Figure 3 (a) (Chen Xu., 2019). designed an automated 3D measurement and detection scheme for the online detection of high-speed train wheel dimensions, using multiple LMI GOCATOR2390 line laser sensors and high-precision 2D rotary tables to form a high-speed rail wheel rotation scanning system. As shown in Figure 4.

Fig. 4. High-speed rail automatic three-dimensional measurement line (Chen Xu., 2019)

Development trends and challenges of 3D measurement technology based on digital twins

Currently, emerging information and communication technologies such as digital twins, cloud computing, the Internet of Things, and big data are rapidly developing, providing new ideas and opportunities for the development of high-end manufacturing. With the rapid popularization of 3D measurement equipment, point cloud processing technology is playing an increasingly important role in it. Therefore, how to achieve the integration and feedback of detection models and CAD design models is a manifestation of digital twin technology in 3D measurement technology, and it is also a technical challenge for 3D online measurement equipment. The three-dimensional measurement technology has achieved automated online quality inspection of industrial parts, which is of great practical significance for improving product quality, reducing energy consumption, and reducing labor costs.

Conclusion

With the arrival of a new round of industrial revolution and the rapid development of artificial intelligence, cloud computing, and the Internet of Things technology, major industrial countries around the world have begun to accelerate the construction of smart factories and lighthouse factories. The 3D online inspection system for parts using machine vision will be an important piece of equipment in the manufacturing and inspection of products in intelligent factories and lighthouse factories. This article first reviews and introduces the key technologies of machine vision and 3D measurement, such as 3D scanning and reconstruction technology, 3D point cloud registration technology, etc. Finally, typical cases of the application of 3D measurement systems in the field of intelligent manufacturing were summarized, and the development trends and challenges faced by 3D measurement systems were discussed.

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Дослідження технології 3D-вимірювання на основі машинного зору

Вимірювання є важливим засобом людства для розуміння та зміни навколишнього світу і це технологічна основа, що забезпечує розвиток передових наукових досліджень та вирішення широкого кола проблем економічного та соціального розвитку. Розвиток та вдосконалення систем 3D-вимірювання служить першочерговим національним потребам, сприяє розвитку національної економіки та є важливим елементом, що забезпечує національної безпеку. З початком нової промислової революції великі індустріальні країни світу почали прискорювати стратегічне розгортання інтелектуального виробництва. Важливим компонентом будівництва високоінтелектуальних виробничих підприємств є система 3D-вимірювання, яка має відігравати важливу роль у поглибленні реалізації стратегії виробництва та просуванні високоякісного, інтелектуального та екологічного виробничого процесу. В останні роки технологія оптичного 3D-вимірювання, представлена поверхневим структурованим світлом, швидко розвинулась і отримала застосування в багатьох областях обробки матеріалів, таких як кування, лиття та обробка листового металу. Для проведення аналізу точність виготовлення складних деталей за допомогою технології 3D-вимірювання зі структурованим світлом поверхні, на першому етапі необхідно виконати сканування та реконструювати загальну 3D-поверхню деталі. Отримані внаслідок реконструкції тривимірні дані хмари точок поверхні деталі мають бути узгоджені з проектною моделлю. На наступному етапі виконується порівняння даних та аналіз точності у відповідності до заявлених технічних вимог на контрольовану деталь. У цьому процесі точність реконструкції тривимірної поверхні складної деталі та точність кореляції між результатами реконструкції та проектною моделлю безпосередньо визначають надійність і точність остаточного виготовлення деталі та аналіз точності обробки. У цій статті розглянуто приклади, які ілюструють застосування машинного зору в 3d-вимірюваннях. Застосування технології 3d-вимірювання в системах активного контролю якості, наприклад, при шліфуванні лопатей може не тільки підвищити точність вимірювань оброблених деталей, але також дозволить забезпечити високу продуктивність та відносну стабільність сили різання при обробці лопатки турбіни авіаційного двигуна на автоматичному шліфувальному роботі. Наведено приклад застосовування технології 3d-вимірювань при онлайн-інспекції якості втулок коліс поїздів, адаптерів коліс поїздів і розміру коліс високошвидкісного поїзда.

Ключові слова: *цифровий двійник, машинний зір, 3D-сканування та реконструкція, реєстрація 3D хмари точок.*