Multi-View Structured Light 3D Measurement System

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DOI: 10.12142/ZTECOM.202404008

https://kns.cnki.net/kcms/detail/34.1294.tn.20241105.1427.004.html, published online November 6, 2024

Manuscript received: 2023-10-22

Abstract: Vision-based measurement technology benefits high-quality manufacturers through improved dimensional precision, enhanced geometric tolerance, and increased product yield. The monocular 3D structured light visual sensing method is popular for detecting online parts since it can reach micron-meter depth accuracy. However, the line-of-sight requirement of a single viewpoint vision system often fails when hiding occurs due to the object's surface structure, such as edges, slopes, and holes. To address this issue, a multi-view 3D structured light vision system is proposed in this paper to achieve high accuracy, i.e., Z-direction repeatability, and reduce hiding probability during mechanical dimension measurement. The main contribution of this paper includes the use of industrial cameras with high resolution and high frame rates to achieve high-precision 3D reconstruction. Moreover, a multi-wavelength (heterodyne) phase expansion method is employed for high-precision phase calculation. By leveraging multiple industrial cameras, the system overcomes field of view occlusions, thereby broadening the 3D reconstruction field of view. Finally, the system achieves a Z-axis repetition accuracy of 0.48 μm.

Keywords: 3D measurement; structured light; multi-view

Citation (Format 1): LU P, ZHANG Y J, DENG F W, et al. Multi-view structured light 3D measurement system [J]. ZTE Communications, 2024, 22(4): 53 – 58. DOI: 10.12142/ZTECOM.202404008
Citation (Format 2): P. Lu, Y. J. Zhang, F. W. Deng, et al., "Multi-view structured light 3D measurement system," *ZTE Communications*, vol. 22, no. 4, pp. 53 – 58, Dec. 2024. doi: 10.12142/ZTECOM.202404008.

1 Introduction

Efficient quality inspection of workpieces plays an important role in manufacturing. Thus, there is a growing demand for full-featured quality inspection methods. Traditionally, the primary quality inspection method used in manufacturing is 2D machine vision, which relies on industrial cameras and computer vision algorithms. This method has been beneficial in past years due to its elemental precision and effectiveness for various production tasks. However, 2D machine vision is increasingly inadequate for achieving higher production efficiency in the context of rapid advancements in intelligent manufacturing. 2D machine vision can only inspect the two-dimensional aspects of workpieces, such as length, width, and radius. These measurements alone are insufficient for evaluating more complex workpieces. In today's global economy, quality inspection increasingly requires capabilities such as hole detection and elevation measurement. As the focus shifts from 2D to 3D, the assessment scale expands significantly. Therefore, machine vision now plays a crucial role in quality inspection.

Traditional machine vision technology based on 2D image processing has revolutionized industrial production, manufacturing processes, product testing, and other fields. However, intelligent manufacturing imposes higher requirements for machine vision technology. Traditional 2D machine vision is susceptible to light conditions, cannot measure the three-dimensional dimensions of space, and relies on manually adding input parameters, which are inadequate for the further development of intelligent manufacturing. In contrast, 3D vision[1] can measure flatness, angles, position, and other three-dimensional dimensions, making it the trend for automatic detection in intelligent manufacturing.

2 Recent Research on Structured Light Measurement

There has been extensive research on 3D shape measurement based on structured light. In the industrial field, products like the KEYENCE LJ8000 series and LMI 2600 series

This work was supported by the 2023 Guangdong Basic and Applied Basic Research Fund Regional Joint Fund Key Project under Grant No. 2023B1515120017, 2023 Key Project of Guangdong Provincial Department of Education for General Universities under Grant No. 2023ZDZX3024, and ZTE Industry-University-Institute Cooperation Funds under Grant No. K2133Z167.

utilize line laser profile meters. These systems require highly precise moving equipment to achieve accurate regional dimensional measurements. However, the limitation of the angles of incident and reflected light can lead to occlusions and the missing point cloud, particularly with workpieces that have stairs and height differences. To address these issues, different movements and angles are necessary, but this often results in decreased precision with longer working distances and wider line widths. These products generally have an accuracy of a few microns.

Recent research has been conducted to improve the efficiency of 3D machine vision measurement. A temporally encoded structured light system was used to obtain accurate 3D measurements[2]. This system took into account lens distortion in both the camera and projector, which are key components of the structured system. The proposed method could achieve an average measurement error of approximately 1 mm. Additionally, a multi-view structured light system has gained attention. A stereo vision method for 3D measurement method was proposed to develop an automatic measurement system, which enhanced measurement accuracy to about 0.1 mm[3]. One study suggested grouping two arbitrary cameras into a single system, allowing each group to generate data into a universal coordinate[4]. This approach further improved the measurement accuracy to around 0.02 mm. Moreover, binary defocusing technology has been used in 3D structured light measurement to accelerate the process. An improved method that combines 1D and 2D fringe modulations was introduced, helping to improve both efficiency and accuracy[5]. This method can reduce measurement errors by 16.9%.

From the research results above, we can find that there is no proven technique for 3D machine vision shape measurement at the microns level[6]. The best-achieved precision in 3D machine vision technology remains about 1 micron, with no further breakthroughs reported[7–8]. The current mainstream solution to machine vision uses mono or stereo cameras to reconstruct the surface. However, there is still an empty area in the multi-camera for structured light to solve the larger measurement view. Besides, it is necessary to speed up the reconstruction to adapt to the production task.

This work focuses on high-precision 3D machine vision measurement using a multi-lens structured light system, alongside optimizing the point cloud reconstruction algorithm for experimental demonstration.

For the multi-lens structured light system, calibration accuracy greatly determines and affects the system's accuracy during 3D measurement. Therefore, achieving high-precision system calibration is a key challenge for the system designed in this project. In addition, processing the large amounts of data obtained from high-resolution cameras poses difficulties. The data must be filtered to remove environmental noise and redundant information, which is essential for improving processing speed while maintaining measurement accuracy. Furthermore, enhancing detection speed and efficiency is necessary to meet the demands of industrial production.

The monocular structured light and passive optical measurement schemes mentioned above are greatly affected by the interference of ambient light. The visual field of the monocular vision measurement system can be easily blocked by irregular objects. In scenarios involving high drops, there can be issues such as violent data jumps. Improvements are necessary to meet the measurement requirements for real time, high efficiency, and high precision in the 3C electronics manufacturing industry, particularly for electronic chips and precision electronic components, as well as for packaging chips and printed circuit boards (PCBs) made of materials like plastics, ceramics, and glass with low reflectivity. The proposed method has the following improvements:

1) We use a four-mesh high-resolution camera to generate multi-view images, which ensures data processing speed and partially addresses the occlusion problem. Our algorithm can also be used to optimize data redundancy and information overlap.

2) We adopt a high-resolution blue-ray projection module with a 459 nm wavelength to minimize ambient light interference and provide a high-brightness measurement light source for the structured light measurement system.

3) We utilize a sinusoidal grating coding scheme with multi-frequency heterodyne and a four-step phase shift method to unwrap the sinusoidal phase, avoiding phase calculation errors caused by binarization and increasing the system's robustness against surface texture interference.

3 Methods

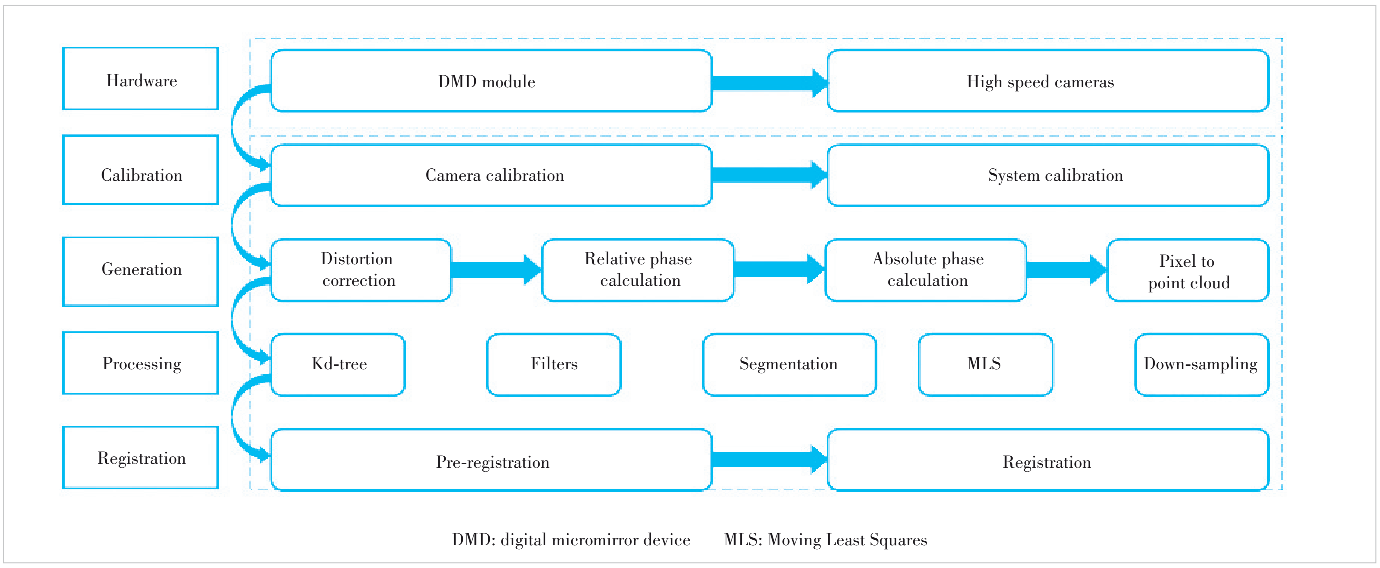
To realize the high speed and high accuracy of 3D measurement, a system that combines high-resolution cameras with projector modules is proposed in this paper. Multi-cameras in this system use the redundancy of point cloud data from individual structured light systems to enhance accuracy. The multi-camera setup can also fill the missing area obscured by workpieces in a single structured light system.

In this section, we introduce sequential projection and other post-processing methods. Fig. 1 describes the flowchart of the system setup from hardware to algorithms.

3.1 Sequential Projection

The measurement techniques include sequential projections, continuously varying patterns, and others. Compared to other techniques[9], sequential projections have higher accuracy than some alternative methods. However, they need to project a sequence of patterns, which requires the objects under test to be stabilized for better measurement results. Sequential projections can be categorized into different types, including binary codes, gray codes, and phase shifts. The primary focus of this work is the phase shift method[10].

The phase shift method uses a set of sinusoidal patterns to



▲Figure 1. Proposed system setup formed by hardware and software

facilitate 3D reconstruction. The intensities for each pixel (x, y) of the three projected fringe patterns are described as follows:

$$I_1(x, y) = I_0(x, y) + I_{mod}(x, y)\cos(\varphi(x, y) - \vartheta), \tag{1}$$

$$I_2(x, y) = I_0(x, y) + I_{mod}(x, y)\cos(\varphi(x, y)), \tag{2}$$

$$I_3(x, y) = I_0(x, y) + I_{mod}(x, y)\cos(\varphi(x, y) + \vartheta), \tag{3}$$

where $I_1(x, y)$, $I_2(x, y)$ and $I_3(x, y)$ are the intensities of three fringe patterns. $I_0(x, y)$ is the direct current (DC) component (background), $I_{mod}(x, y)$ is the modulation signal amplitude, $\varphi(x, y)$ is the phase, and ϑ is the constant phase-shift angle.

Phase expansion converts the wrapped phase to the absolute phase. The phase information $\varphi(x, y)$ can be retrieved from the intensity in the three patterns[11]:

$$\varphi' = \arctan\left[\sqrt{3}\frac{I_1(x, y) - I_3(x, y)}{2I_2(x, y) - I_1(x, y) - I_3(x, y)}\right]. \tag{4}$$

3.2 Improved Calibration Methods

In terms of calibration methods, the mainstream is to use ZHANG's method[12] because of its simplicity and robustness. However, this method also has its disadvantages. In a structured light system calibration process, the projected patterns are used to boost calibration. The chessboard calibration board is always used to extract the corners. However, if the boards are covered with sinusoidal patterns, accurately extracting these corners becomes challenging due to interference from the patterns. To address this issue, an improved calibration method uses a circle calibration board instead of a chessboard. This approach allows for clearer separation of the circle points from the background, facilitating easier extraction of the corner points regardless of the existence of projected patterns. Fig. 2 shows that the circle calibration board outperforms the chessboard calibration board in terms of reprojected errors of the extracted corners. We can see that the black-and-white chessboard calibration board in Fig. 2 has the highest phase change, while the circle calibration board shows the lowest phase change (the ideal phase is constant in a single line).

3.3 Point Cloud Processing Algorithm

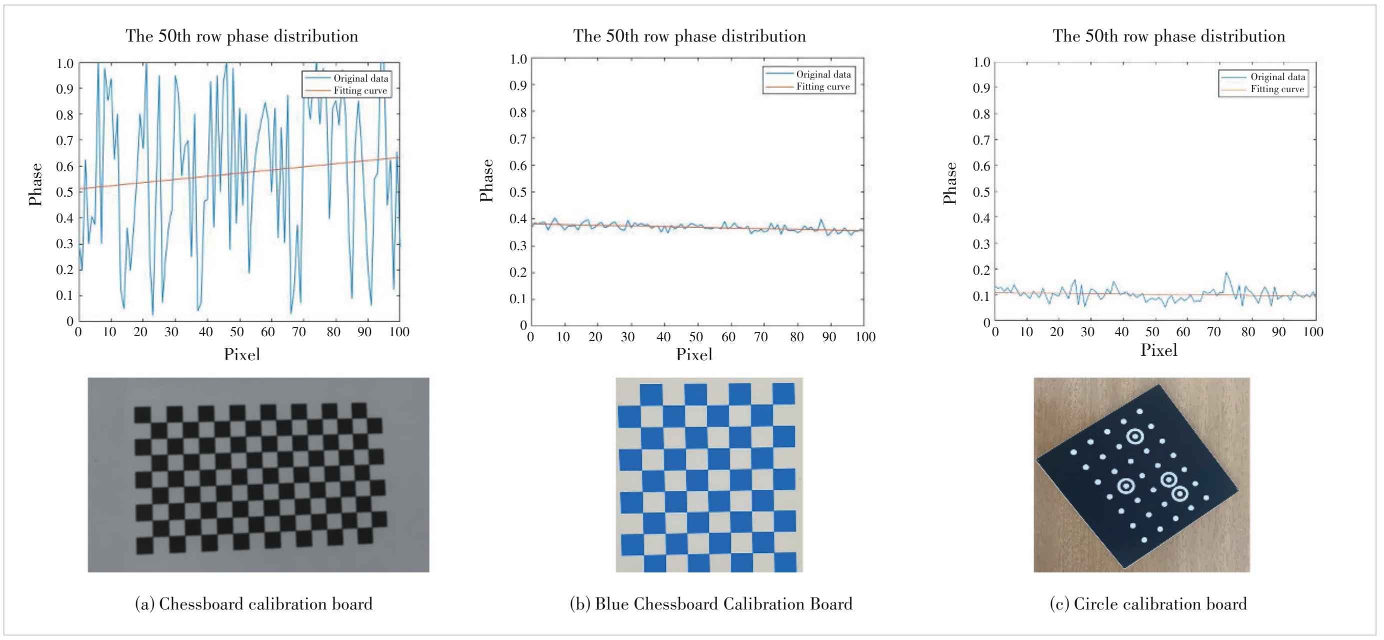
After generating the point clouds, processing methods and algorithms are more important in the industrial field. In the context of this work, the coplanarity calculation method is proposed.

During the PCB production process, sometimes the pins on PCBs may be skewed due to human disturbance or assembly errors. Therefore, it is important to find out whether the pins are vertical or not. To find the coplanarity of the pins on the PCBs, the analysis software should locate the top surfaces of the pins. The plane formulations are obtained by fitting the points of the top surfaces with the random sampling and consensus (RANSAC) algorithm or the least mean square method. All pins' surface plane formulations can calculate the distances between each other. The difference between the maximum and minimum distances represents coplanarity, which indicates the fluctuation of pins.

4 Experiments

4.1 Hardware System Setup

To realize the high resolution and high measurement frequency in 3D reconstruction, the camera performance must be



▲**Figure 2. Different calibration board´s phase distribution**

reliable. Therefore, we chose four Basler CoaXPress 2.0 boA5320-150cm cameras (each with a resolution of 16 MP) and the DLP4710 module with a resolution of 1 080P for projection. In this way, the DLP module can achieve a frequency of up to 120 Hz for projected patterns, enabling the camera to capture frames immediately as they are projected. This hardware selection helps to enhance the system's performance.

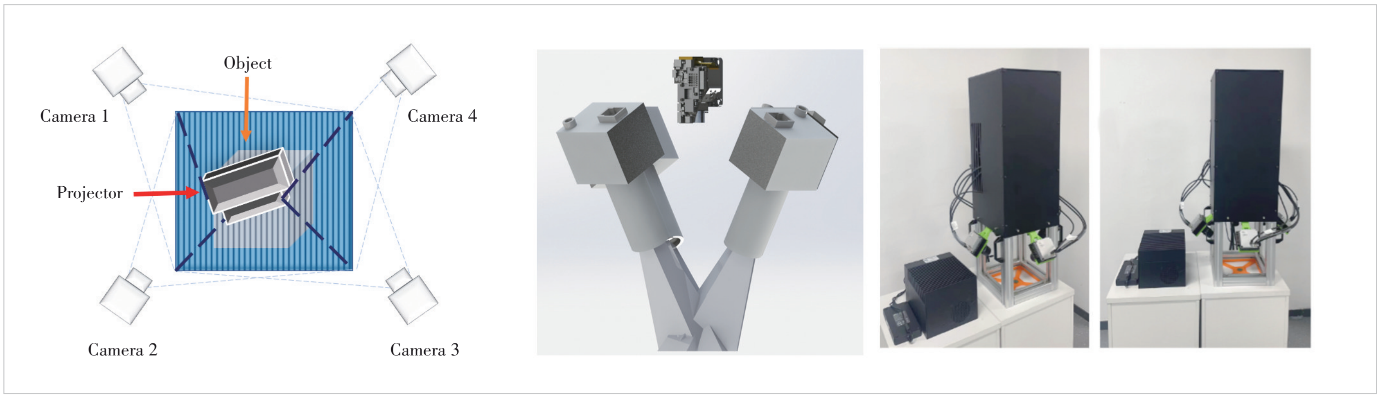
In the real measurement situation, the objects under test are about 6 cm×9 cm. To make the cameras' view cover the object, the overlapped field of view must be larger than the object itself. This allows the four cameras to capture the images of the object. We designed a multi-camera system and used SolidWorks to simulate the overlapped field of view to find the optimal measurement. The 3D module and simulated results are shown in Fig. 3.

4.2 System Workflow

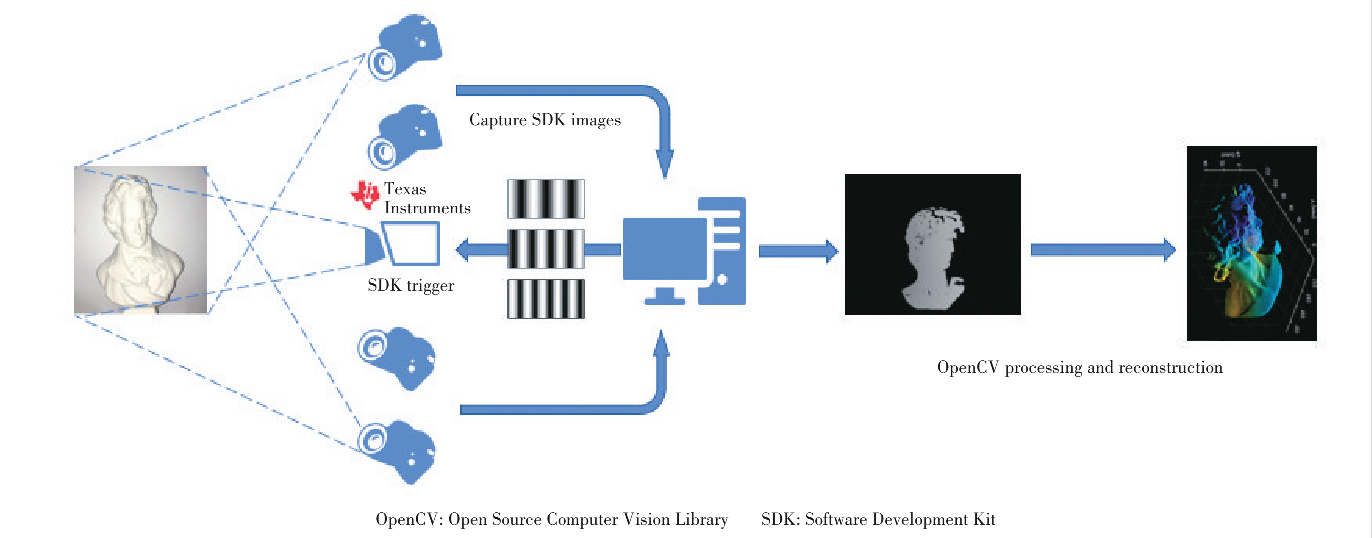
The main workflow of this work is shown in Fig. 4. Once the tested object is placed within the view field of the system, the PC is triggered to execute the measurement program. The projector projects a set of sequential sinusoidal patterns and triggers the cameras simultaneously. The triggered cameras capture the images and transmit them to PC for further processing. Using calibration parameters and processed images, the PC reconstructs the test object in the form of point clouds.

4.3 Experiment Results

Table 1 shows the experiment results with different workpieces, which contains the DIY PCB (PCB 1), the actual power supply module (PCB 2), and other test samples. The results were compared to the coordinate measuring machine (CMM) and the Mega Phase 3D structured light camera M051090, and the measurements from CMM were compared to the real values. The experiment demonstrated that with our equipment, the repeatability error calculated using Root Mean Square (RMS) reached 0.001 mm in actual measurements, and



▲**Figure 3. Hardware setup for the experiments**



▲**Figure 4. Workflow of the proposed multi-view 3D structured light vision system**

▼**Table 1. Different tested objects and their measurement results**

Tested Objects	Our Method/mm	Our Method RMS/mm	CMM/mm	CMM RMS/mm	M051090/mm	M051090 RMS/mm
Cellphone middle frame	0.446 5	0.001 53	0.454 0	0.000 82	0.447 1	0.001 85
	0.444 7		0.455 2		0.448 4	
	0.445 0		0.453 4		0.447 8	
	0.444 3		0.453 4		0.446 3	
	0.448 0		0.453 2		0.447 9	
Ceramic ball	19.993 4	0.000 15	20.004 5	0.000 04	20.014 5	0.000 31
	19.993 7		20.004 5		20.015 6	
	19.993 6		20.004 6		20.015 3	
	19.993 8		20.004 5		20.016 1	
	19.993 6		20.004 5		20.016 4	
PCB 1	7.226 2	0.015 15	7.258 8	0.007 81	7.296 6	0.017 21
	7.259 2		7.263 0		7.272 4	
	7.238 2		7.257 2		7.282 8	
	7.228 0		7.274 5		7.299 8	
PCB 2	7.304 9	0.040 76	7.302 8	0.030 59	7.328 9	0.044 17
	7.259 2		7.326 0		7.381 2	
	7.311 9		7.372 9		7.398 9	
	7.358 8		7.352 4		7.415 9	

CMM: Coordinate Measuring Machine PCB: Printed Circuit Board RMS: Root Mean Square

the absolute error reached 0.01 mm, which is more accurate than the measurements from M051090.

As shown in Table 1, the proposed system performs well in real industrial situations, and the RMS error is reliable and stable compared to the results from CMM.

5 Conclusions

The proposed system uses high-speed cameras and high-frequency projectors to achieve high accuracy in 3D reconstruction and measurement. The experiment results show that the system's repeatability and accuracy meet the requirements of real manufacturing situations when compared to the CMM and M051090. The proposed system works out the accuracy problem in the 3C industrial field and provides insights when measuring irregularly shaped objects using multiple camera systems.

In future, the proposed system can be further improved into a more integrated form and the cameras' view can be enlarged by switching to wider-view lens. Moreover, the system aims to become more autonomous for industrial applications.

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