Measurement Method for Geometric Parameters of Small Module Gears Based on Machine Vision

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Abstract: *The number of teeth, diameter of the indexing circle, tooth top height, root circle diameter, pressure angle, and tooth top circle diameter are commonly used parameters in the process of detecting qualified gears. The measurement of small module gears has always been a challenge in industrial applications due to the difficulty of manual measurement and the significant difference between the measurement results and actual data. In response to the problems of high statistical error rate and low efficiency in measuring the geometric parameters of small module gears, this paper studies the contour characteristics of small module gears based on machine vision (MV) and explores measurement methods for morphological features. A new image acquisition method is proposed to address the phenomenon of gear overlap and the varying sizes of diameter, length, and pitch density. A real-time analysis system for automatic parameter measurement data of small module gears is designed, ultimately achieving research on automatic measurement of small module gears. This study conducted experiments on gear images obtained from industrial cameras. The proposed automatic measurement method for small module gears was found to have a maximum error of 0.0043mm through traditional microscopy and measurement using the system. The measurement results of geometric parameters of 8 sets of gears demonstrate that compared to other methods, the automated measurement of small module gears in this paper has better calculation accuracy and processing speed. It can more accurately obtain the geometric parameters of small module gears in bulk, providing technical support for future small module gear measurement related work and helping the development of related industries.*

Keywords: *Small Modulus Gears, Measurement of Geometric Parameters, Machine Vision, Gear Parameters*

1. Introduction

In the industrial field, gears as an important part of the power transmission, its quality for the performance and stability of mechanical equipment plays a vital role. To ensure the quality and reliability of gears, the manufacturing process requires a series of rigorous testing and control measures. The measurement of geometric parameters of gears has an important impact on quality control, process processing, and fault diagnosis in industrial production. At present, there are three main tools used for measuring gear geometric parameters in China: gear measuring instruments, coordinate measuring machines, and optical measuring instruments. These devices have certain advantages in measuring gear geometric parameters, but there are also some disadvantages, such as high cost. The cost of purchasing and maintaining high-precision measurement equipment is relatively high, which may be difficult for some small and medium-sized manufacturing enterprises to afford. This high-precision measurement equipment usually require operators who have undergone professional training to operate, and the operation process is relatively complex, requiring a certain level of technical proficiency and experience. Simultaneously using these devices for measurement takes too long, this can be a bottleneck in the production cycle for gear manufacturers producing in large quantities, greatly reducing production efficiency. In industrial production applications, due to the differences in gear shape characteristics, single precision measurement equipment is prone to missed measurements, reverse direction, and mechanical damage to parts. MV based mechanical seeding has the advantages of high precision and high efficiency, which aims to break through the development bottleneck of small module gear parameter measurement and achieve mechanization and automation of industrial gear production.

In the field of computer vision, determining the coordinates of the transmission center is important because it directly affects the accuracy of transmission parameter measurements. In traditional image recognition methods, center detection algorithms are usually focused on the center point or central area of the image. However, these methods have some limitations. For example, the first two methods require a uniform distribution of images, and the latter requires point-to-point matching, which can take time and cannot meet the accuracy requirements of industry standards. To solve these problems, this paper proposes a mathematical morphology method to automatically analyze transmission parameters. Specifically, gear images are input into a computer and gear features are extracted using an image processing algorithm. The method can effectively separate gears from complex backgrounds and realize automatic counting and measurement of tooth dimensions. Practice shows that the method has achieved good results in practice. It not only improves the measurement accuracy, but also significantly improves the working efficiency. For industrial applications that require precise measurement of transmission parameters, the mathematical morphology method has high practical value.

This article is based on the research goal of detecting the geometric parameters of small module gears, referring to previous research, and constructing a new detection algorithm system based on MV. The usability of the system was ensured through precision testing and repeatability testing. A new detection method has been contributed to the geometric parameter detection of small module gears, which is beneficial for improving the efficiency of industrial gear production and application.

2. Related Works

There have been relevant studies in the field of detecting gear geometric parameters. Tan Q et al. designed a structured light system consisting of a laser linear light source and a camera to measure the shaft diameter. This method not only improves the accuracy of the measurement, but also ensures the reliability of the measurement results. Highly accurate shaft diameter measurements are realized, providing strong support for industrial manufacturing and quality control. Finally, he successfully designed a gear detection system with a correct shaft diameter measurement model and a measurement accuracy that meets engineering requirements [1]. In the context of detecting gear surface integrity, an innovative machine vision cascade inspection method has been proposed by Dong L et al. This method aims to comprehensively localize and identify thermal damage on the tooth surface after the grinding process. Finally, Dong L et al. confirmed the high utility and effectiveness of the proposed method in real-time inspection during gear machining through practical validation [2]. This research result not only improves the accuracy and efficiency of gear surface integrity inspection, but also provides new ideas and tools for quality control in the whole machinery manufacturing industry.

Similarly, based on MV measurement methods, Liu G et al. conducted a considerable number of durability tests on polyformaldehyde (POM) gears using a gear durability test bench under adjustable load and lubrication conditions. He developed a novel reliability model based on machine learning and used this dataset to evaluate the contact fatigue reliability of POM gears [3].

These research results provide new visual measurement and reliability evaluation methods for the gear manufacturing field, playing an important role in improving product quality and production efficiency. However, there is a lack of exploration in the study of geometric parameter testing methods for small module gears. Small module gears have always been a challenge in gear parameter measurement due to their small volume, high precision, and difficulty in manual measurement. Based on this, this study explores the geometric parameter measurement method of small module gears based on MV, in order to provide practical solutions and improve the efficiency of industrial production and use of gears.

3. Methods

3.1 Machine Composition

In this paper, the geometric parameter measurement system for small modulus gears is designed in such a way that in addition to the software system, there can be an external system to assist the measurement, including a platform charge coupled device (CCD) camera, a light emitting device (LED) light source [4], an optical system, an image acquisition card, and a computer. The overall structure of the system is that the gears are placed flat on the platform and illuminated from the top by LED light sources, providing basic and uniform illumination for each gear. The optical device below the camera has target zoom and autofocus functions. The image acquisition card is installed in the interconnect slot of the peripheral components of the computer and connected to the camera through a communication bus. Software components are installed on computers running Windows XP [5]. This software includes an image processing program for image control acquisition and image analysis. The system software can be described according to image processing, mainly including modules such as source image grayscale transformation, image filtering, image segmentation, morphology processing, parameter analysis and statistics, result information display, and data storage.

The following figure 1 shows the specific system description of the hardware part of the small modulus gear geometric parameter measurement measurement system designed in this paper, through the external hardware system can collect the experimental gear image to complete the test for the machine vision system.

The conversion of 24 bit color images captured by CCD cameras to 8-bit grayscale images improves processing speed. Image filtering is used to filter out noise generated during image acquisition and improve image quality. Image segmentation is used to separate gears from their background. Morphological processing is mainly used to obtain information about the center and number of teeth of gears. The parameter analysis module is used for gear parameter processing, outputting the number of possible faulty gear teeth. The result display section of the software uses histograms and pie charts to display the results [6]. From the overall structure of the measurement system, it can be seen that the system is mainly composed of an image acquisition module, an image preprocessing module, and a parameter measurement module. By using a combination of algorithms that execute these functions and features, gear measurement tasks can be efficiently and accurately completed.

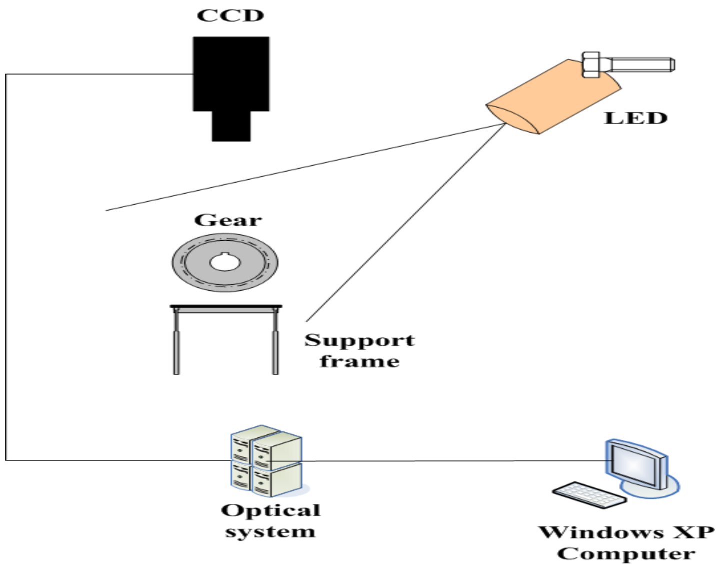

Figure 1: External hardware components of the measurement system

3.2 Preprocessing of Gear Images

1) Grey transformation

Due to the fact that images are captured by cameras in the form of color images, grayscale gradient processing should be performed when digitizing images to improve computational speed. Using the principle of sensitivity of the human eye to different colors, the study obtained the following equations [7] by weighting and then averaging the image parameters.

$$Y = \omega_R \times R + \omega_G \times G + \omega_B \times B \tag{1}$$

ω_R, ω_G and ω_B correspond to color components R, G, and B, respectively, and Y is the pixel value of the corresponding point on the grayscale image. Due to the highest sensitivity of the human eye to green, followed by red and finally blue, better grayscale images can be obtained. By setting $\omega_G > \omega_R > \omega_B$, ω_R=0.30, ω_G=0.59, and ω_B=0.11, the grayscale of the

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image is 255. Before finalizing the grayscale image, study taking the reverse image of the image to continue using it. The formula used to obtain the inverse image is (2).

$$J(x,y) = 255 - I(x,y) \tag{2}$$

Through the original image of the gear grayscale conversion to further complete the entry of the image of the wheel, the following figure 2 and figure 3 shows the effect of the original image of the gear after grayscale conversion.

Figure 2: Original image of gears

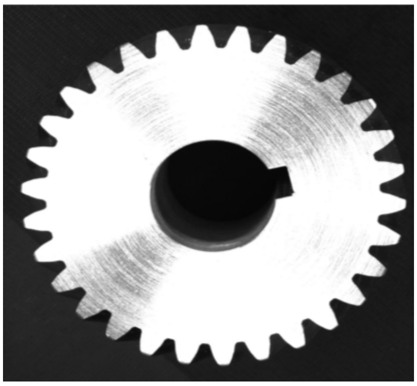

Figure 3: Gray scale transformed image of gears

2) Noise reduction

In order to eliminate any noise generated during the image acquisition process, the median filtering method is studied. It is based on non-linear signal processing technology for sorting and statistical theory, which can effectively suppress noise. The basic principle is to use a sliding window containing odd pixels, replacing the grayscale value of the central pixel in the window with the median of the grayscale values of the points contained in the window [8].

Firstly, determine an odd pixel window, and when each pixel within the window is sorted by grayscale, replace the pixel value at the center of the window with the grayscale value at the middle position. It can be represented by the following formula:

$$g(x,y) = median\{f(i-k,\ \mathrm{j}\text{-}l),(k,l) \in W\} \tag{3}$$

W is the selected template or window size, usually chosen as 3 × 3. 5 × 5 or 7 × 7. In order to better express its working principle, this study added some noise points to the source image.

According to the above arithmetic steps further the gear gray scale map is noise reduced to remove the light points of the image and the noise reduction result is shown in Figure 4.

Figure 4: Noise reduction results

3) Image binarization

Binarization utilizes the difference in grayscale features between the extracted target image and its background, treating the image as a combination of two regions (target and background) with different grayscale levels. The key to distinguishing these two regions is to choose a reasonable segmentation

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threshold [9]. When the grayscale value of a pixel exceeds this threshold, the pixel belongs to the target. Otherwise, it belongs to the background. In the gear image being processed, there is only one target and one background, and the grayscale distribution of the target and background is more uniform than before. Then, the result of image binarization can be displayed as a bimodal curve on the histogram. Selecting a threshold T between two peaks allows the pixels of the image to be divided into two parts: the group of pixels with grayscale values greater than T (target) and the group of pixels with grayscale values lower than T (background). In order to improve the adaptive ability of the system, the paper adopted the iterative threshold method [10]. This means selecting an approximate threshold as the initial estimate value, and continuously improving this value to generate subgraphs using the initial values. This article selects a new and better threshold based on the characteristics of the sub images. Then, it uses this new threshold to segment the image, resulting in better segmentation results than using the initial threshold. In this paper, the following equation can be obtained by binarizing equation (4):

$$g(x,y) = \begin{cases} 0 \; f(x,y) \geq T \\ 1 \; f(x,y) < T \end{cases} \tag{4}$$

F (x, y) is the original image, g (x, y) is the binary image, and T is the threshold. The part of the image with a specified value of 1 represents the target gear, and the part with an assigned value of 0 represents the background (Figure 5).

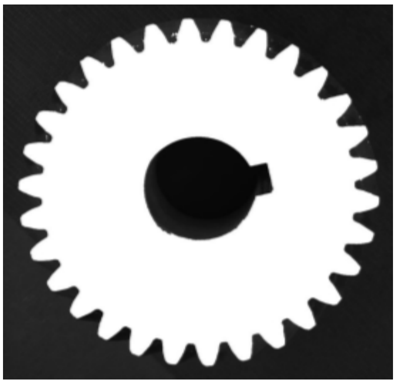

Figure 5: Binarization diagram

3.3 Parameter

1) Morphological processing

Based on the analysis of image samples collected on site, binary gear images have holes that must be eliminated using filling algorithms. This algorithm is defined in the following paragraph [11]. The first step is to input the binary image generated during the preprocessing stage and initialize some parameters. It can start from a point inside the polygon area and fill it with the selected color until people encounter the boundary [12]. The boundary is specified by a single color, so the seed filling algorithm is used to process pixel by pixel until the boundary color is encountered. Seed filling algorithms typically use four connected and eight connected domains to perform filling operations. Starting from any point within the region, all pixels in the region can be reached through eight adjacent pixels located at the top, bottom, left, right, top left, bottom left, top right, and bottom right corners. This article uses these adjacent pixels, and the entire region is recursively filled.

2) Determine the center

As the basis of transmission parameter measurement, the accuracy of the transmission center plays a decisive role in the overall measurement accuracy [13]. In this paper, the center calculation method is considered. First, a binary image must be input. Then, the device target is recognized. Next, the system searches and tracks the coordinates of the device target to find the edge of the test gear. Once the edge is found, the point furthest from the edge is recognized, forming the smallest convex polygon with the gear. By connecting these coordinate points, this convex polygon can be drawn and its perimeter and area calculated. Finally, the article performs rounding level detection for gear images. Suppose the circumference of the gear is C and the area of the gear is A. This results in the roundness value of the measured gear:

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$$E = \frac{4\pi A}{C^2} \tag{5}$$

If the roundness class E < 0.9, the gear is considered to be deformed and no operation is performed. The circular curve is fitted, after which, using the fitted circle, the toothed top circle with center and radius rH is calculated. After the gear has been mounted, the top and bottom tooth circles can be determined. The calculation formulas are as follows:

$$\begin{cases} x = x_0 + r\cos\theta \\ y = y_0 + r\sin\theta \end{cases} 0 \le \theta \le 2\pi \tag{6}$$

(x_0, y_0) is the center coordinate obtained from step⑧. When r=rL, the bottom circle of the tooth can be obtained, and when r=rH, the top circle of the tooth can be obtained.

The algorithm of the machine vision-based geometric parameter measurement system for small modulus gears is built, and the overall flow is shown in Figure 6. In order to prove the practicability of the whole measurement system, the study next carries out real-life preset experiments on the system.

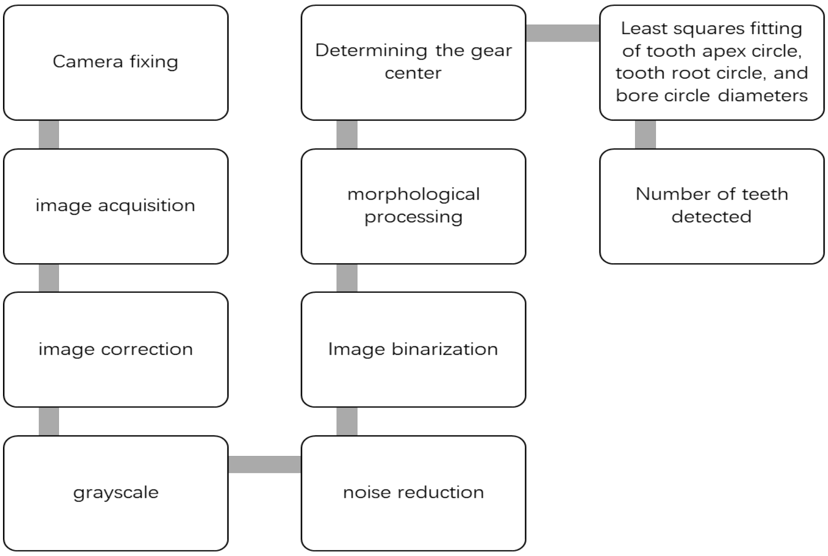

Figure 6: Test system workflow

4. Results and Discussion

4.1 Preset Experiment

In order to verify the effectiveness of the proposed method, experiments were conducted in this study. In the experiment a 1280×1040 pixel CCD camera was used with a unit area of 4.068×3.686 mm. The whole experiment was conducted as follows: First, a calibration step was performed. This step uses a standard block to calibrate the measurement system, then it can make the system K = L/L_0, and determine its ratio to 0. L denotes the measured computer image size and L_0 is the standard size of the block [14]. The size of the image is measured in pixels and the measured size of the measurement block is calculated in millimeter units. In particular, the measured size was calculated as L_2= 1. Finally, the standard size was compared to the measured size to determine if remain within the error interval allowed by the experimental results. The measurement results are shown in Table 1.

Table 1: Measured data of geometrical parameters of experimental gears

Parameters	Number	Upper radius(mm)	Bottom radius(mm)	Modulus
Traditional method	12	40.1	31.0	2
Proposed method	12	40.8	30.6	2

For the system and the external hardware of the system after restoring the initial values, the

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measurement of the experimental gears was started. The study uses the traditional microscope to measure the small modulus gears, the measurement value obtained by this method can provide a more standardized measurement value as a comparison value for the system measurement, the data in the table are obtained. It can be seen that the difference between the two values is within 1mm, which shows that the system is very accurate, and it can be used instead of the manual measurement to realize the large-scale gear parameters of gears on a large scale instead of manual measurement.

4.2 Repeatability Testing

By using this system to measure the same tooth on the test piece 8 times, and then comparing the data, the analysis results of measurement repeatability can be obtained. The measurement parameters of the test piece are shown in Table 2.

Table 2: Repetitive experimental test results (mm)

	1	2	3	4	5	6	7	8	Standard deviation of measurement
Tooth thickness	0.997	0.992	1.020	1.017	1.021	1.010	1.004	1.009	0.009
Tooth pitch	1.877	1.855	1.846	1.866	1.848	1.872	1.853	1.872	0.011
Common normal length	4.481	4.505	4.469	4.472	4.488	4.478	4.488	4.492	0.010

According to the measurement results in Table 2, this article uses the Bessel formula [15] to calculate the repeatability standard deviation. It can be concluded that the repeatability standard deviation of the three gear parameter measurement results is less than or equal to 0.011mm, taking the repeatability test of tooth pitch as an example. This article presents a line chart as shown in Figure 7, which clearly indicates that the tooth pitch of the test gear is between 1.846mm and 1.877mm, indicating a high measurement repeatability of the system.

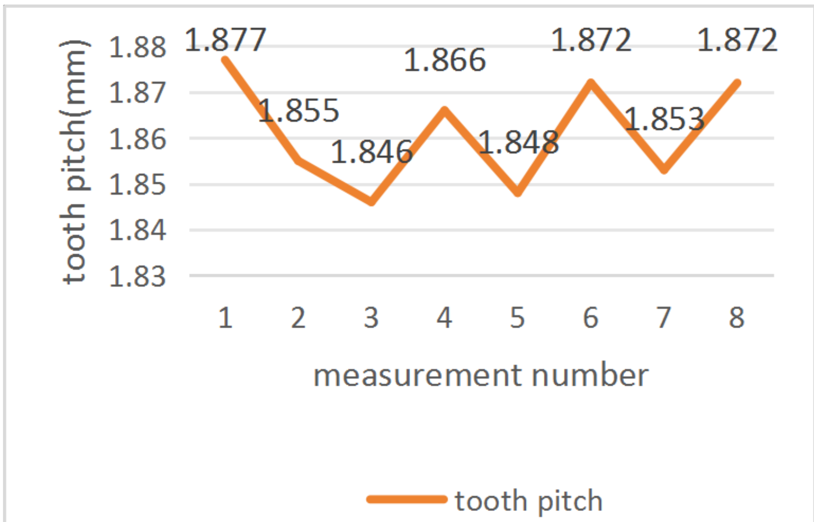

Figure 7: Line graph of tooth pitch repeatability test

4.3 Measurement Accuracy Experiment

This article washed the tested gear with alcohol, wiped it clean with a dust-free cloth, and placed it on the system loading platform. It adjusted the two-dimensional manual platform so that the gears are within the visual system's field of view. It used measurement software to measure the geometric parameters of gears, while using a universal tool microscope to measure the diameter of the tooth tip circle and the diameter of the tooth root circle as a control.

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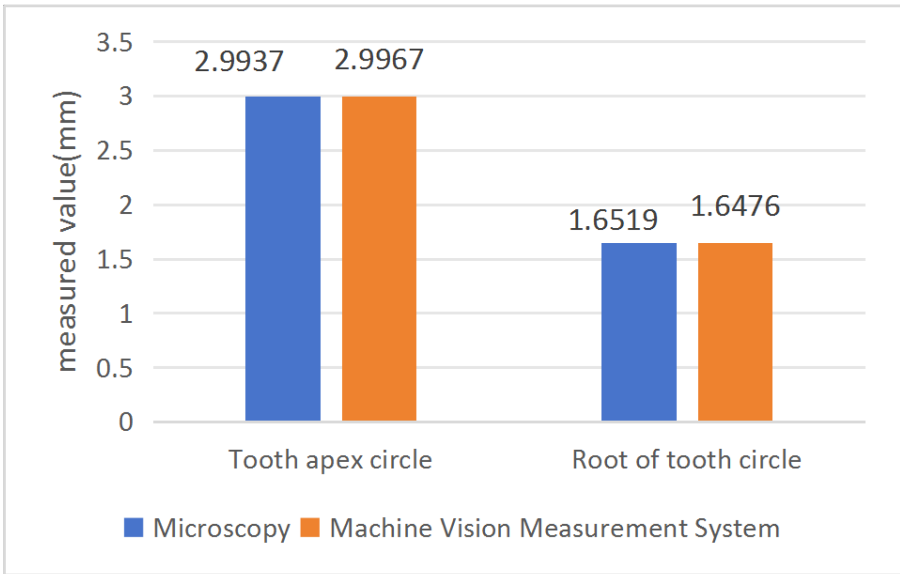

Figure 8: Error visualization

As shown in Figure 8, the measurement results show that the diameter of the tooth tip circle measured by the microscope is 2.9937mm, and the diameter of the tooth root circle is 1.6519mm. The visual measurement system designed in this article measures a tooth tip circle diameter of 2.9967mm and a tooth root circle diameter of 1.6476mm. The absolute errors in measuring the tooth top circle and tooth root circle are 0.003mm and 0.0043mm, respectively. The statistical results indicate that the maximum error of the measurement system in this measurement is 0.0043mm, and the measurement results are relatively accurate. On the one hand, it depends on the accuracy of calibration, and on the other hand, it indicates the superiority of the system, which to some extent reflects the reliability of the measurement algorithm.

5. Conclusions

Gears are indispensable for much mechanical equipment, and the functionality and lifespan of the entire equipment are determined by the accuracy of the gears. Due to the large variety of types and complex contour shapes, gears have various parameters and error detection items, making them still a hot research topic. With the rapid development of industrial technology, the precision and efficiency requirements for measuring gears are also increasing, and the requirements for measurement technology are also increasing. High precision and high speed measurement are inevitable requirements for the development of future measurement technology. The emerging MV technology has also received widespread attention and application from various sectors due to its advantages of high flexibility, non-contact, high efficiency, and high adaptability.

This article studies a batch rapid measurement method for small module gears based on MV. In order to achieve high-precision and high-efficiency measurement of batch small module gears based on MV, a high-precision calculation method for gear center coordinates in visual measurement is proposed, which helps to reduce measurement errors caused by center point calculation errors. During measurement, there is no need to align the center position of the measured gear, which improves measurement efficiency and accuracy. During the process of collecting gear images, multiple small module gears can be placed simultaneously in the same field of view, and the image connected area extraction algorithm can be used to separate each gear, achieving the goal of batch and rapid detection of small module gears. This article builds a hardware platform for measuring small modulus gears and designs a software system for measuring small modulus gears. Through this experimental platform, the geometric parameters and individual deviations of small modulus gears are measured. It verifies the high-precision calculation method of gear center point coordinates and the feasibility of using tooth profile data points near the gear indexing circle to fit circular arcs instead of gear involutes for calculating tooth pitch deviation.

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