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基于虚拟仪器的宏微复合光栅尺测量系统

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摘　要:为适应微电子制造装备中精密位移反馈装置的要求,提出并设计了一种新型宏微复合光栅尺测量系统.测量系统采用 LabVIEW 虚拟仪器系统高速采集图像数据,通过图像处理算法对放大后的光栅栅纹进行边界处理,将其细化为线再转化为像素点,并补偿运动过程中的微量位移来提高精度.实验结果表明:电机速度为 1 mm/s,行程为 100 mm 内时,该系统产生的位移误差可控制在 1.5 μm 内,分辨率可达 0.275 μm.与传统光栅尺测量中需对莫尔条纹进行电子细分相比,本测量系统可以有效消除光栅尺破损、污染、倾斜、光源不稳定等干扰给测量带来的影响,同时保持微米级别的测量精度,特别适用于敞开式光栅尺长行程的测量领域.

关键词:精密测量;宏微复合;数字图像;光栅尺;莫尔条纹;虚拟仪器;位移测量

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Measurement System of Macro-micro Composite Grating Ruler Based on Virtual Instrument

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Abstract: In order to meet the requirements of precision displacement feedback devices in microelectronics manufacturing equipment, a macro-micro composite grating ruler measurement system is proposed. First, the LabVIEW virtual instrument system is used for image data acquisition with high-speed. Then, the boundary of the amplified raster grating pattern is turned into lines with image processing method, which are later converted into pixel points, and the micro displacement in the motion process is compensated to improve the accuracy. The experiment results show that the proposed system can be used to keep the displacement error to 1.5 μm and the resolution to 0.275 μm with the motor speed of 1 mm/s and the distance of 100 mm. Compared with the traditional grating ruler measurement with moiré fringe electronically subdivided, the proposed measurement system can effectively eliminate the interference, such as grating scale damage, pollution, tilt and light source instability, on the measurement while maintaining the micron-level measurement accuracy, which is especially suitable for the long-distance measurement of open-scale grating ruler.

Key words: Precision measurement; Macro-micro composite; Digital image; Grating ruler; Moiré fringe; Virtual instrument; Displacement measurement

OCIS Codes: 120.0120; 120.1880; 120.2650; 110.0110; 110.2650

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0 Introduction

Precision measurement tools are used extensively in numerical control machines, mechanical and electronic integration equipment, industrial robots and other fields[1-3]. With the discovery of the moiré fringe and the development of grating measurement technology, the grating ruler, which uses the optical grating principle to perform precise line or angular displacement measurements, has been commonly used as a displacement feedback device in precision measurement[4-6]. For example, the grating ruler is used to detect the coordinates of the tool and workpiece in the Computer Numerical Control (CNC) machine, as well as to observe and track the cutter error in order to compensate for tool motion error[7-8]. In microelectronic manufacturing equipment, the grating ruler is also used to detect faults in the printed circuit online. The traditional measuring technique of the grating ruler involves the collection, subdivision and calculation of the moiré fringe by means of an electronic circuit under the illumination of a light source so as to obtain the displacement and judge the motion direction[9-11]. However, the measurement speed is restricted by the complex conditions of high resolution and accuracy, and the high resolution increases the difficulty of electronic circuit subdivision which requires a highly controlled working environment and is easily disturbed by external factors[12].

At present, with the rapid developments in computers and mathematics, digital image processing technology has played a much important role for expanding applications in aerospace, robotics, industrial control and other fields. Also, this technology is used in dynamic measurement of grating ruler [13-16].

Virtual instrument technology has the function of simulating the real instruments, which utilizes modular hardware and flexible software to complete the application of various testing, measurement and automation. The most representative system of virtual instrument technology and products is National Instruments (NI)[17-18]. LabVIEW is a development environment of a graphical programming language developed by NI. It is an engineering software that is specially designed for testing and controlling applications. Users can not only apply powerful functions to design Human Machine Interface (HMI) that meet their requirements, but also quickly access the hardware and read data, select high cost performance industrial control computers and acquisition cards and sensors for online programming, test measurement, and engineering control[19-20].

In this work, virtual instrument and digital image processing technology are combined for application in the precision measurement field to measure the grating ruler displacement, which can be operated-controlled in real time and observed-debugged online. The proposed method is stable, accurate and feasible, and is particularly suitable for measuring the dynamic displacement of the grating ruler. Furthermore, it offers a new, accurate measurement method, which is much less affected by complex conditions, for researchers in the measurement and detection field.

1 Test system set-up and algorithm implementation

1.1 Test system set-up

This system uses the LabVIEW software to construct an image acquisition and displacement detection device with a PXI chassis, an image grabber, an optical imaging module, and a precision motion platform. The system hardware equipment includes a CMOS camera, an image acquisition-processing module, an objective lens, a coaxial microscope tube, a light source, an incremental grating ruler with a 40 μm pitch, and a display. The grating ruler is fixed on the precise motion platform of the linear motor and synchronized with the platform . Under the irradiation of a parallel light source, the magnifying grating image is acquired by an objective lens. There

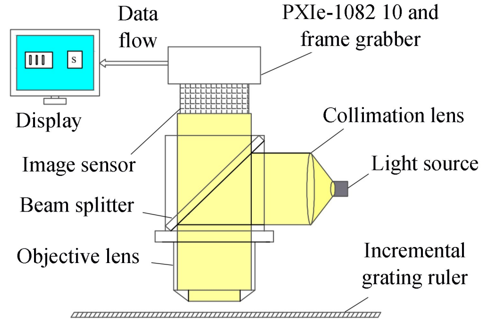


Fig.1 Schematic diagram of the grating ruler measurement system

after the image acquisition card transfers the collected image information to the signal-processing module on the LabVIEW software platform, which is equipped with a PXI chassis. The images are recorded, subdivided and calculated, in order to present the real-time grating ruler displacement on the display. The principle of the optical test illustrated in Fig.1.

1.2 Implementation of macro-micro composite measurement

1.2.1 *Image preprocessing*

In this system, the first step involves processing the mono images obtained by the acquisition card. The system uses the flexible online design of LabVIEW to obtain the camera Region of Interest (ROI), and then transforms the elements of the binary image digital matrix $\boldsymbol{A}_{m\times n}$ into a Boolean matrix $\boldsymbol{B}_{1\times n}$ after setting a threshold value.

$$\begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ a_{n1} & a_{n2} & \cdots & a_{mn} \end{bmatrix} \rightarrow [a_{11}+a_{21}+\cdots+a_{n1} \quad a_{12}+a_{22}+\cdots+a_{n2} \quad \cdots\cdots \quad a_{1n}+a_{2n}+\cdots+a_{mn}] \xrightarrow{\tau} [b_{11} \quad b_{12} \quad \cdots \quad b_{1n}] \tag{1}$$

Here, the rows and columns represent the number of pixels corresponding to the ROI length and width, respectively. The maximum and minimum elements in the matrix A_1 after summing by column is $A_{1\max}$ and $A_{1\min}$, and the threshold τ is

$$\tau=(A_{1\max}+A_{1\min})/2 \tag{2}$$

The elements in the matrix $\boldsymbol{B}_{1\times n}$ are respectively

$$b_{1i}=\begin{cases}1, & b_{1i}>\tau \\ 0, & b_{1i}\leqslant\tau\end{cases} \tag{3}$$

The continuous element 0 corresponds to the grating fringe, and the continuous element 1 corresponds to the spacing between two grating fringes in $\boldsymbol{B}_{1\times n}$. It is assumed that the first and last columns of the continuous element 0 in matrix $\boldsymbol{B}_{1\times n}$ are p and q, and the corresponding positions of m_1(the median lines) of grating fringes in the matrix $\boldsymbol{B}_{1\times n}$ are

$$m_1=\frac{p+q}{2} \tag{4}$$

1.2.2 *Macro-micro composite measurement*

Next, the macro-micro composite measurement algorithm is proposed that the macro measurement displacement is obtained by counting the median line of a specific matrix $\boldsymbol{B}_{1\times n}$ location. When the median line is in the same column as the count location, by counting a median line, the fixed count position is a column fixed determined in a matrix. And the displacement of macro measurement is

$$S_1=(N-1)\times W, N>0 \tag{5}$$

where N is the number of median lines, W is the pitch of grating ruler.

Furthermore, the micro measurement is the sum of two parts in the index matrix in the ROI: one is the distance between the fixed count position and the nearest median line of the count position, S_{21}, as shown in Fig. 2(a), and the other is a median line leaving the fixed count position, S_{22}, as shown in Fig. 2(b). For example, in the ruler motion direction of as shown in Fig.2, there are k_1 and k_2 pixels of the median line in the index area near the count position. k_1 and k_2 are the minimum column values corresponding to the median lines in the matrix at the start and stop time respectively, and the micro measurement displacement is

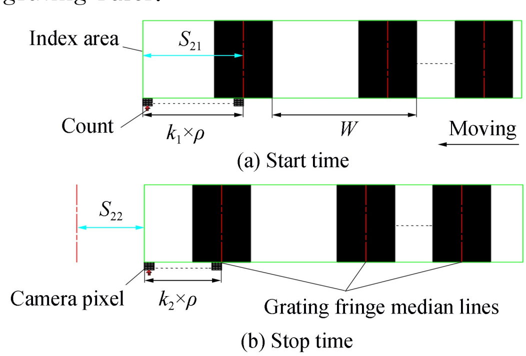


Fig.2 Schematic of displacement measurement

$$S_2=\begin{cases}(k_1-k_2)\times\rho, & N=0 \\ k_1\times\rho+(W-k_2\times\rho), & N>0\end{cases} \tag{6}$$

And the motion displacement is

$$S = S_1 + S_2 \tag{7}$$

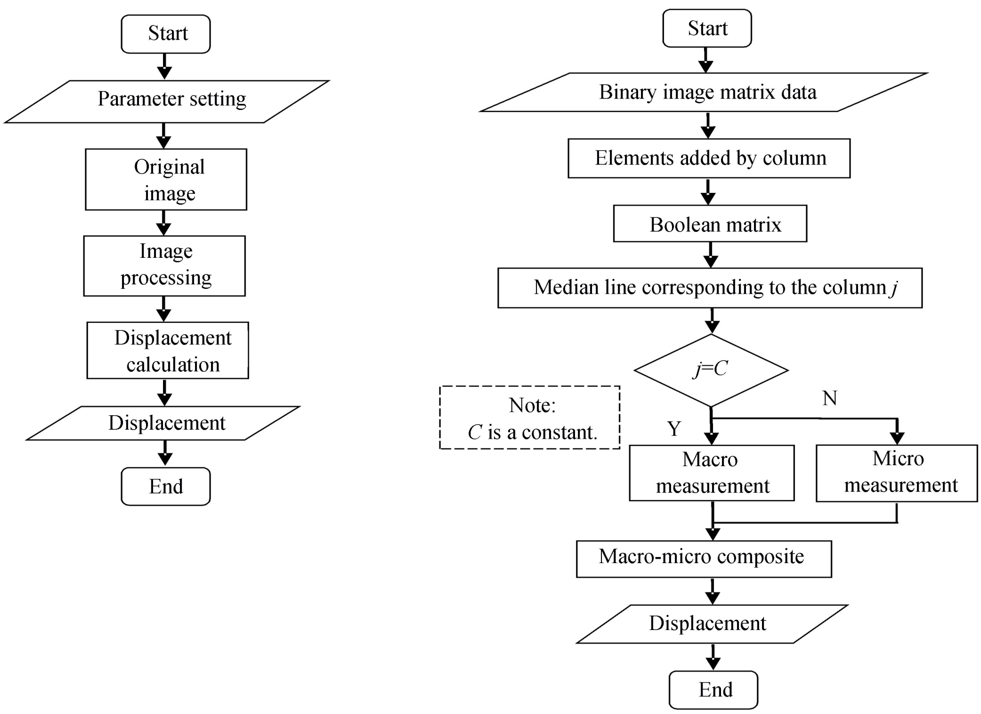
The maximum resolution δ is

$$\delta = \frac{\rho}{2X} \tag{8}$$

where ρ is the camera image sensor pixel size, and X is the magnification of objective lens.

2 Experimental study

Software design of the test system on LabVIEW that includes the front panel of HMI and the back panel-block diagram program. The front panel includes panel operation of analog instruments, and it controls the device by the corresponding command parameters of the frame, device interfaces and other settings. Furthermore, the image and displacement data of grating ruler can be displayed and monitored in real time in the front panel. The program flowchart as shown in Fig.3(a). After the image binarization, a binary image is obtained, according to the algorithm described in Section 1, the algorithm of macro-micro composite measurement is designed as the flowchart in Fig.3(b). And the system is programmed and debugged by the block flow diagram on back panel as shown in Fig.4.



(a) LabVIEW program (b) Algorithm of macro-micro composite measurement

Fig.3 Flowcharts

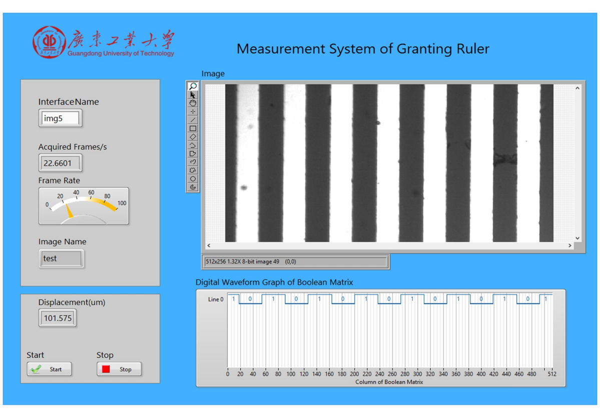


Fig.4 The front panel of virtual measuring platform for grating ruler displacement

By the imaging preprocessing which is proposed in Section 1.2.1, the median lines of grating fringes have turned into corresponding columns in Boolean matrix, as shown in Fig.5. With the movement of the grating ruler, the corresponding columns in the Boolean matrix are also moving. Finally, the motion of the grating image (plane motion) is transformed into lines and then change into points motion. And the measurement accuracy is improved by compensating the trace displacement between the distance of the grating pitch.

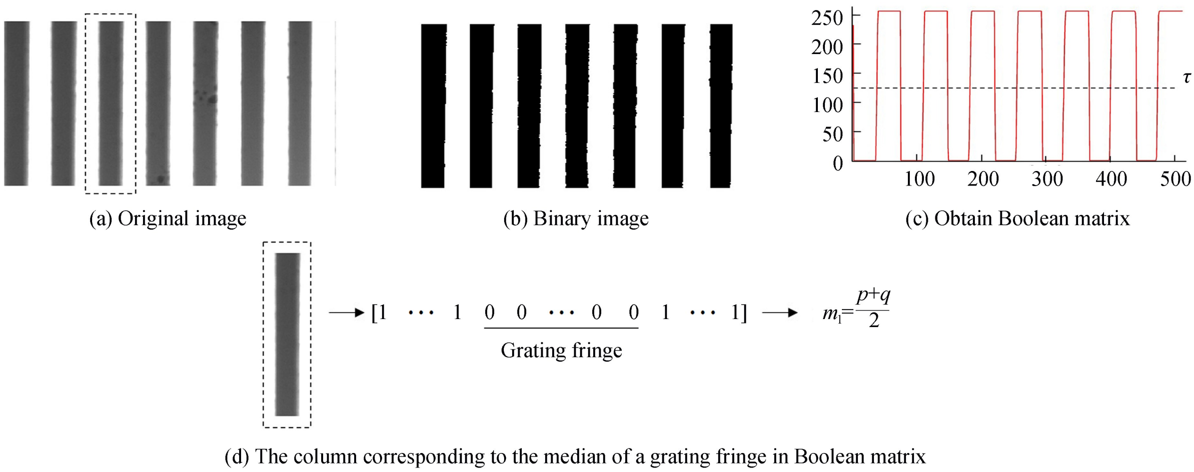


Fig.5 Illustration of analysis of the measurement

The system shown in Fig.6 is setup to validate the above novel method. The motor tested platform itself contains a 20 μm pitch RGS20-PC of Renishaw grating ruler. The results of the displacement detected by the proposed method is compared to the traditional method using counts of moiré fringes and subdivision. In the experiment, by giving different motor speeds, the results of the test system displacement are recorded repeatedly. And the laser interferometer RENISHAW XL-80 is used as a comparison of the corresponding record displacement with ±1.5 μm.

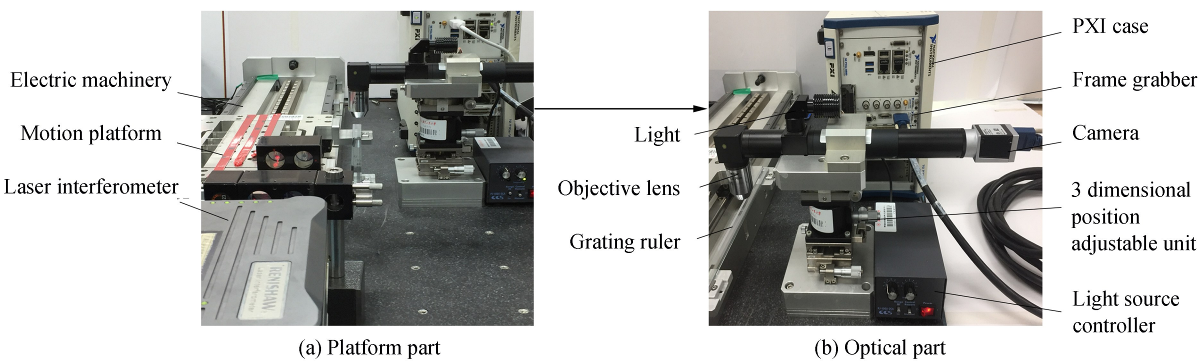


Fig.6 Test system for the proposed macro-micro composite of grating ruler

The grating images are received by using an image acquisition device of NI PXIe-1435 and a CMOS array with 2 048× 2 048 pixels of Basler ace acA2040-180 km, the size of the CMOS sensor pixels is 5.5 μm×5.5 μm, and the ROI of this system is 512 × 256. According to the spectral response of the camera, a red light with wavelength range of 620～760 nm is selected. The test system employs an objective lens (10×), and an adjustable light intensity light source controller to verify the test results under different light intensity . All the experiments have done in

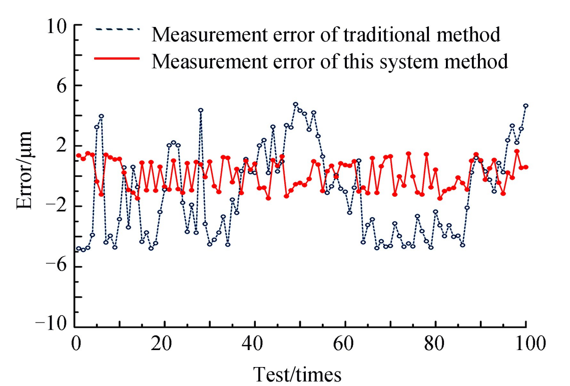


Fig.7 Measurement errors obtained by different method

dynamic condition, where the vibration is reduced by the marble platform. The measurement is operated with the speed increased from 0 by the motor. A group of data is tested, the analysis of the displacement results is shown in Fig.7.

As the results shown in Fig.7, compared with the traditional method, the proposed macro-micro composite measurement method can obtain relatively stable measurement accuracy, and its measurement error is less than 1.5 μm. However, the measurement accuracy of the traditional method is intensely volatility and its maximum error is up to 5 μm. With the statistical analysis, the standard deviation of the novel method is 0.95 μm, which is much less than 2.97 μm that of traditional method, it proves that the measurement accuracy obtained by the proposed method is significantly improved compared to the traditional method.

3 Data analysis and discussion

Traditional grating measurement technology can be easily interfered by external factors. For example, the grating ruler may be polluted and damaged during manufacturing and long-term use, especially in open gratings. Also, light source unevenness, grating ruler installation error, temperature changes, vibration, and other factors cause the electrical signals fluctuations and introduce errors into the measurement system. In the experiment, the errors of this system originate from the micro displacement measurement and manufacturing error of the grating ruler.

The camera acquisition of the incomplete and tilted grating ruler images is illustrated in Figs.8(a) and (b), the angle of the grating fringe is 1°. Fig.8 shows that the damage or contaminate exists in the boundary or part of the grating image. According to the proposed method, the edgeis extracted with the digital image matrix element in the ROI. As shown in Figs.8 (c) and (d), this method can effectively filter out the interference information such as contamination and damage of grating ruler, while the tiny inclination of the grating ruler does not affect the extraction of the grating boundary. Then the median lines of the gratings are obtained by the continuous element 0 in Boolean matrix which corresponded to the column in the matrix shown in Figs.8 (e) and (f). Thereafter, by repetitious experiments, the obtained median lines distance under different light intensities are compared with the number of pixels corresponding to a theoretical pitch in Table 1. The number of pixels corresponding to the grating with a 40 μm pitch is 72.7.

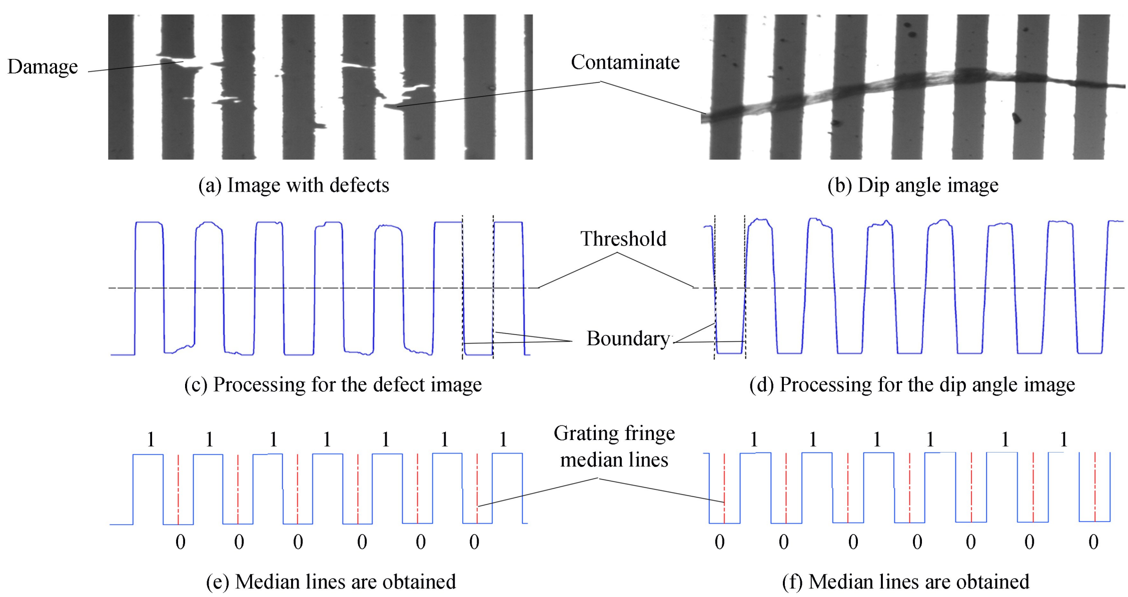


Fig.8 Analysis of the images

Table 1 Measurement error of median lines with different light intensity

Light intensity/lx	Average value	Theoretical value	Maximum error
400	72.64	72.7	0.8
2 000	72.65	72.7	0.7
3 000	72.73	72.7	0.8

With the novel method of macro-micro composite measurement, there are no errors of counting median lines in macro measurement, but the micro measurement error which leads to errors in the reconstructed midline, consequently resulting in displacement error, arises from the grating boundary detection. Moreover, micro measurement, which does not cause a cumulative error, is compensated between two continuous median lines. Table 1 obviously shows that the spacing between the grating fringe median lines maximum error is no more than 1 pixel, and the standard deviation is less than 0.5 in different conditions. In this paper, the grating fringes are amplified and then refined into lines, so the movement of grating ruler turns into a point movement. Furthermore, the method of setting different thresholds by adding pixel matrix by columns plays an important role in filtering and denoising, and increases the robustness of our measurement system, particularly in the case of strong interference.

4 Conclusion

The proposed measurement system of a macro-micro composite grating ruler based on a virtual instrument includes an acquisition system designed by applying the LabVIEW virtual instrument system for high-speed acquisition image data and a novel algorithm using the image processing method to perform the boundary processing of the amplified raster grating pattern into lines. The study provides accurate experimental results, which are obtained from the laser interferometer, the novel system and the traditional system, to compare different measurement systems. The result shows that the measurement error of the proposed macro-micro composite measurement is less than 1.5 μm while the measurement error of the traditional method is up to 5 μm. It proves that the measurement accuracy obtained by the proposed method is significantly improved compared to the traditional method. Moreover, the proposed measurement system can effectively solve the grating scale damage, pollution, tilt, light source instability and other interference to the measurement.

Overall, the presented novel systemcan make full use of advanced computer hardware, software, and digital image technology, in order to obtain higher development efficiency and more complete system functions. The online measuring system of the grating scale displacement can directly process, transform, and calculate using the magnified grating ruler image on the virtual instrument. Future work will involve applying this method to a dedicated processor, constructing a system and testing with a linear array camera, in order to reduce computation time and increase the measurement range.

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