REVIEW ARTICLE

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Patent Review of Optical Mold External Surface Inspection Methods

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Abstract: Optical mold external surface inspection is a key link in the manufacturing industry, which is vital to ensure the quality of the mold and the final performance of the product. With the rapid development of high and new technology, the modern precision manufacturing industry and surface metrology have also made rapid development, and at the same time, the development of advanced surface measuring instruments, the separation of surface topographic features and the evaluation of the characteristic parameters of the technology to develop a higher level. Advanced measuring instruments are hardware platforms and prerequisites to ensure the precision measurement of surface topography, and surface topography feature separation technology provides effective means and methods for the separation of different micro-geometric contour features; the formation of surface topography is due to the small geometric features in the processing by the combined effect of many random factors. It usually consists of roughness, corrugation and facing accuracy, which affects the performance of the whole equipment and its components. In this paper, we mainly review the patents on the inspection methods of facing accuracy on the external surface of optical molds, covering several innovative technologies and methods, and summarize some valuable conclusions which will provide more reliable and efficient inspection solutions for the manufacturing industry, enhance the level of quality control of optical molds, and promote the development of the manufacturing industry.

Keywords: Optical surfaces, facing accuracy, waviness, detection methods, contact and non-contact, surface topography.

1. INTRODUCTION

Nowadays, optical molds play a vital role in modern manufacturing and are widely used in electronics, automotive, aerospace and other fields. The quality of their external surface directly affects the quality and performance of products. Therefore, the research and development of optical mold external surface inspection methods have become a very important and active field [1-10]. The study of optical mold external surface inspection methods and their devices is of great significance to ensuring product quality and improving manufacturing efficiency [11].

The development of optical mold external surface inspection can be traced back to the early 1980s when optical microscopes or mechanical stylus were mainly used to scan the mold surface and detect mold surface defects through electronic signals [5]. This method is characterized by low efficiency, strong subjectivity of human judgment and other problems, and cannot meet the demand for high-precision and high-speed detection. In the mid-1980s to the early 1990s, the first batch of optical mold surface inspection systems based on computer image processing appeared, which mainly used image processing technology to analyze and process images to achieve the detection of mold surface defects [12-17]. This method requires extensive manual intervention and operation and is not very efficient. From the mid-1990s to around 2000, with the development of CCD cameras and laser scanning technology, optical mold surface inspection began to develop in the direction of automation. The detection and analysis of defects are realized through digital image processing [18, 19]. This method has the advantages of high speed and high accuracy, *etc*. Since the 21st century, optical mold surface inspection has further developed in the direction of intelligence and adaptive, especially with the use of deep learning, neural networks, and other artificial intelligence technologies that can realize the automatic identification and classification of defects on the surface of the mold; robots, automated production lines and other technologies, to achieve the on-line inspection of the surface of the mold and rapid feedback [20, 21]. The inspection speed and accuracy have been continuously improved, providing reliable support for mold manufacturing and quality management.

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Traditional methods for inspecting optical molds' external surfaces include contact and non-contact [1]. Contact methods use mechanical probes to measure the surface topography of optical molds. However, these methods are prone to damage and contamination of the measured surface because they require direct contact with the sample surface [10, 22]. Non-contact methods mainly use optical techniques, such as reflectance spreaders and diffraction imaging methods, which can avoid damage and contamination of the sample surface. However, non-contact methods are greatly affected by factors such as light source, environment, and object characteristics, and they need help with low measurement accuracy and real-time performance. New inspection methods based on optical principles are emerging with the continuous development of optical and computer technologies. These methods include digital holography, phasor measurement interferometry [1, 2, 11, 18-27], speckle pattern analysis, laser triangulation, *etc.* [2, 28-31]. They have the advantages of non-contact operation, high precision and real-time, effectively solving traditional methods' limitations.

In addition to the above methods, innovative methods for external surface inspection of optical molds have also been proposed. For example, optical molds' surface defects and morphology can be more accurately detected using infrared transient thermography, multi-channel LIDAR technology, and image recognition based on deep neural networks [9, 20]. These developments have further promoted the advancement and application of external surface inspection techniques for optical molds.

The purpose of this review is to summarize and analyze the relevant patent literature in this field, outline the principles, advantages, and disadvantages of various optical mold external surface inspection methods, highlight some representative patent literature, and discuss the current technological trends and potential applications. By reading this review, readers can have a comprehensive understanding of the current status and future trends of optical mold external surface inspection methods, which will provide strong support for technological innovation and application in related fields.

2. PRINCIPLE OF OPTICAL MOLD EXTERNAL SURFACE INSPECTION

The main inspection parameters for optical mold outer surface inspection are the facing accuracy at low frequency and the corrugation degree at medium frequency, and the quantity of facing accuracy and corrugation degree directly affect the clarity and resolution of optical imaging. Surface accuracy refers to the deviation between the surface shape of the optical mold and the theoretical surface shape; if the surface accuracy of the optical mold surface is not high enough, it will lead to imaging aberrations and distortions, affecting the imaging quality [3]. Corrugation refers to the undulation change of the optical mold surface within a certain range, usually evaluated in the 0.1 mm to 1 mm range. If the surface of the optical mold is too rippled, it will lead to light scattering and refraction, blurring and distorting the imaging. Therefore, for high-precision optical molds, it is important to control the facing accuracy and corrugation to improve the optical performance and reliability of the product and to ensure the performance and quality of the product [28-42].

The measurement methods of these two parameters are similar and can be broadly categorized into contact and non--contact according to the detection method. Contact measurement methods include mechanical stylus measurement, optical probe measurement, *etc*.; non-contact measurement methods are divided into optical and non-optical, of which the optical type includes laser interference, triangular, and structured light methods.

The mechanical stylus method is a typical contact measurement method, and its measurement principle is to connect the precision detection stylus with the lever; the stylus is directly in contact with the surface to be measured, and with the undulating movement of the surface contour of the measured surface and movement. Then, the movement signal through the lever is converted into an electrical signal to achieve the purpose of detection [4, 43-47]. Mechanical stylus method due to direct contact with the surface to be measured, with its simple structure, stability and reliability, large measurement range, strong anti-interference ability, higher resolution, *etc.,* are widely used in a variety of occasions [1, 7] and have become the most widely used surface measurement instruments in the industry. The stylus is attached to the surface in real-time, and the roughness [48-51], corrugation, and accuracy [52] of the surface shape cause the stylus to move up and down slightly, which can be converted into an electrical signal by an optical interferometry system, or into an electrical signal using capacitance, strain gauges, *etc* [5].

The contact part of the stylus and its tip are usually a flat or rounded tip terminated pyramid or conical diamond; the stylus conical tip arc radius is generally 2.5 or 10 μm, and the cone angle of 60° or 90° specific parameters can be flexibly selected according to the actual measurement needs [4, 7]. The mechanical structure of the support as the input of the sensor will affect the performance of the entire system. The traditional contact measurement is the most important for the lever-type stylus displacement sensor [53-56], as shown in Fig. (**1**).

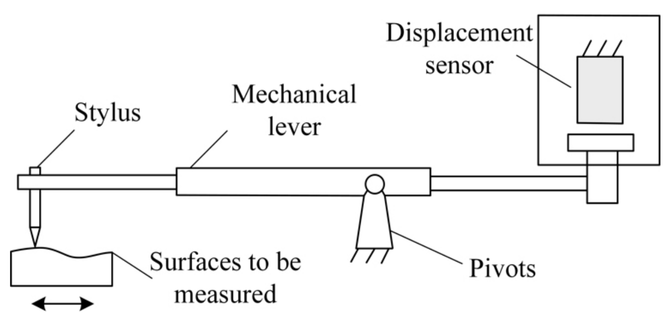

Fig. (1). Lever-type stylus displacement sensor [4].

Contact measurement usually involves a stylus mounted on one end of a lever that undulates with the contour of the surface to be measured and a displacement sensor at the other end of the lever that converts the height information of the surface to be measured into an electrical signal, which is then processed to obtain the information of the surface to be measured. Due to the lever structure, the lever always rotates around its pivot point during measurement. The trajectory travelled by the stylus is a section of the arc, which will inevitably cause measurement error. The measurement error will increase with the increase of the measurement range, which makes the measured contour and the original contour of the part not match [4, 43].

With the maturity of modern technology, especially processing and manufacturing, control, computer and other technologies, the demand for accurate measurement of ultra-precise surface topography is becoming increasingly urgent. Therefore, the mechanical stylus method has also been greatly developed.

In addition to the traditional mechanical lever principle stylus method, the emerging detection methods are divided into inductive, capacitive, piezoelectric, Michelson interferometric, column grating interferometric, scanning white light interferometric, *etc.,* according to the displacement detection principle [57-59], Fig. (**2a**) introduces several common microcantilever mechanical stylus detection methods. The measurement mode is divided into two modes: constant height mode and constant force mode for contact [1, 9, 60-63], and its principle is shown in Fig. (**2a**-**b**).

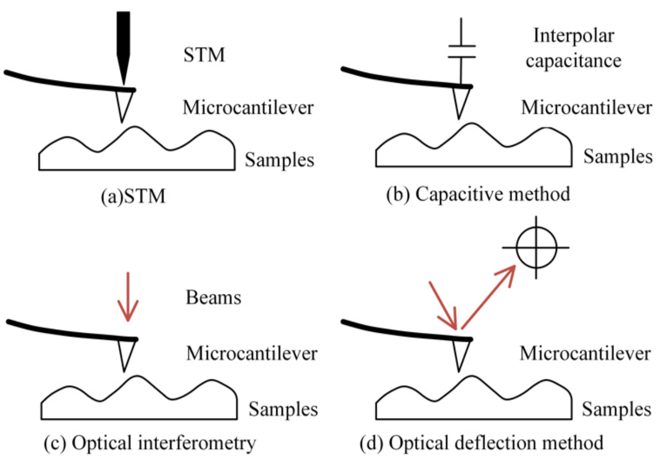

Fig. (2a). Several microcantilever mechanical stylus detection methods (**a**-**d**) [1].

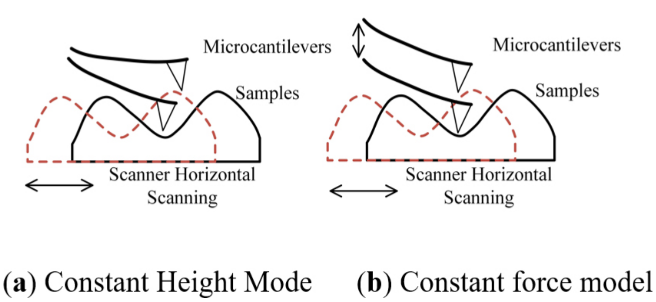

Fig. (2b). Two modes of contact measurement operation (**a**,**b**) [1].

Non-contact measurement refers to the method in which the measurement probe does not have direct contact with the measured object and realizes the surface measurement through light, acoustic wave, air pressure [64], electromagnetic [65] wave and other carriers.This detection method has become the most commonly used detection method because of its extremely fast detection speed and the distance between the measuring head and the part surface is not directly contacted, so it does not scratch the measurement surface; in recent years, the rapid development of the application of a wide range of applications, and the future is still a very great potential for growth [12, 66-68]. The most widely used non--contact measurement methods are optical detection, which includes white light interference, triangulation, and structured light.

Among them, white light interferometry methods are based on the phenomenon of light interference so that when a beam of light hits a beam splitter, part of the light is reflected, and part of the light is transmitted. The reflected beam is reflected when it hits the reference mirror, and the transmitted beam is reflected when it hits the measuring mirror [9, 57-59, 69, 70]. These two light beams interfere in the overlapping region, forming light and dark interference fringes. Differences in the morphology of the measured surface cause differences in the optical ranges of the reflected rays, leading to shifts and changes in the interference fringes. Parameters such as the shape or thickness of the surface under test can be deduced by measuring the movement and change of the interference fringes. Fig. (**2c**) shows the principle diagram of white light interferometry [1].

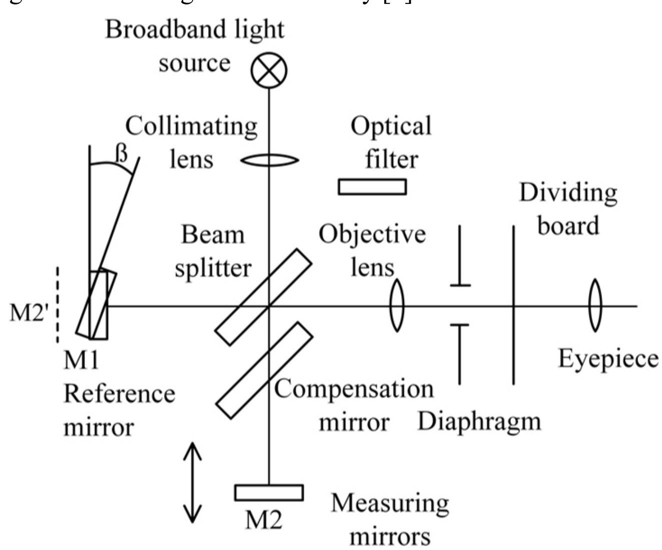

Fig. (2c). White light interferometry principle diagram [1].

White light interferometry can measure surface topography at the nanometer scale with high accuracy. Compared with monochromatic light interferometry, it can measure multiple interference fringes at the same time, which is suitable for surface measurements with large variations in topography. Using suitable optical interferometric instruments can realize rapid automated measurements and improve productivity [1].

Laser triangulation uses a modulated laser beam irradiated to the surface of the object under test. The laser beam scattered on the surface of the object under test is received by the detector and converted into an electrical signal [28-31] by triangulation of the position of the laser beam, the angle and the position of the laser spot received by the detector and other information, the shape of the surface of the object under test can be deduced [1, 71]. Fig. (**2d**) shows the principle diagram of laser triangulation.

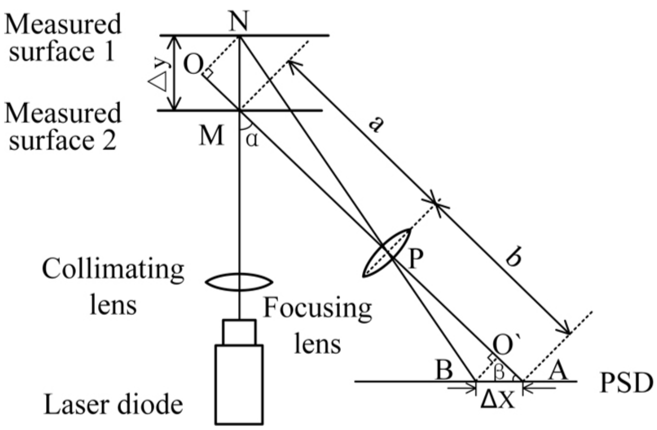

Fig. (2d). Laser triangulation measurement principle [71].

Laser triangulation can be used to measure with high precision and achieve sub-micron surface topography measurement accuracy, especially suitable for the measurement of tiny structures and complex curved surfaces. It can realize rapid automated measurement and is suitable for measuring the surface topography of various objects with different shapes and materials, including metal, plastic, glass, *etc*. It is widely used in manufacturing and quality control, robot navigation, medical imaging and other fields [8].

The structured light method is a commonly used method for 3D topography measurement. The measurement principle uses a light source (usually a laser) [2] to project a specific structured light pattern onto the surface of the object to be measured. The surface shape of the object to be measured causes the light pattern to distort, displace, and other deformations on the surface. A camera or an image sensor is then used to capture the image of the light pattern reflected or scattered by the surface of the object. The three-dimensional topographical information of the object under test can be inferred by analysing and processing the acquired light pattern images. Fig. (**2e**) shows a simple structured light method--Hartmann measurement schematic [72].

The measurement accuracy of the structured light method is not as good as that of white light interferometry and laser triangulation, and only sub-millimetre or higher measurement accuracy can be achieved, which is suitable for precision engineering and manufacturing fields. However, it can realize faster measurement speed, especially based on the integrated projected-acquisition structured light equipment, which can realize real-time or near real-time 3D topography measurement. It is also suitable for surface topography measurement of various objects with different shapes and materials, including metal, plastic, glass, *etc*. The structured light method can be adapted to the measurement tasks of different scenes and requirements by adjusting the parameters such as the structure, angle and frequency of the projected light pattern [3].

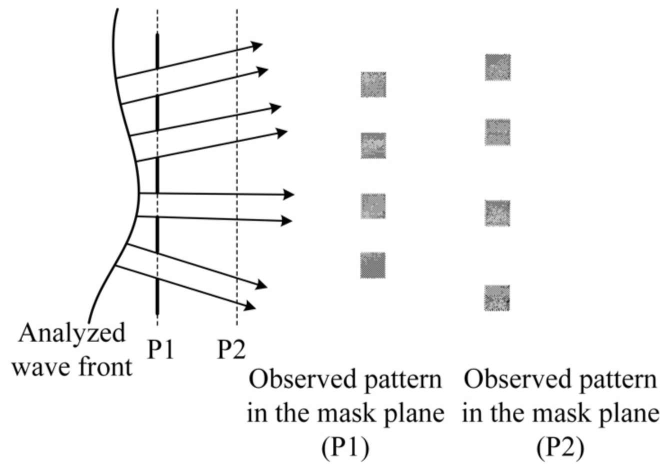

Fig. (2e). Principle of the Hartmann test [72].

It should be noted that the structured light method also has some limitations and sources of error, such as lighting conditions, the nature of surface reflections, and occlusion, which may affect the precision and accuracy of the measurement results. In practical applications, technical means such as multi-view fusion and texture enhancement can be adopted to improve the reliability and accuracy of the measurement. The structured light method has a wide range of applications in industrial manufacturing, virtual reality, robot navigation, cultural relics protection and other fields.

3. INTRODUCTION OF PATENT FOR STYLUS SURFACE INSPECTION

The mechanical stylus method is the most classical contact measurement method; with the continuous progress of computer technology, microelectronics technology, sensor technology and automation technology, the mechanical stylus method also continues to develop to obtain higher accuracy and reliability, widely used in actual production [4].

Y.M. Lang, C.G. Fang, and P. Cao of Harbin Gauge and Sharpening Tool Group [43] invented a grating lever structure stylus displacement sensor. This patent is a grating-type lever structure stylus displacement sensor, using the stylus scanning method to measure the two-dimensional shape of the surface of the workpiece distance, angle, arc radius and other parameters; the core component is used to collect the measured surface contour information of the stylus sensor. The core component is a stylus sensor that collects information about the surface profile to be measured. When this sensor is used for measurement, the relative displacement between the scale of the reading grating system and the grating read-head is generated, and the stylus displacement is converted into an electrical signal output from the grating read--

head to obtain the parameter of the surface profile to be measured. The sensor panel is equipped with a switch between manual or automatic pen lifting action control. The measuring force is manually adjusted by moving the stylus's adjustment weights.

The main advantages of this invention are compact structure, small size, ease of installation, stable and reliable measurement results, and ability to achieve a resolution of 0.1-micron high-precision measurements in the full range of measurement range of several tens of millimetres, but also according to the work of the flexible control of the size of the measurement force [43]. The structure of the device is shown in Fig. (**3a**).

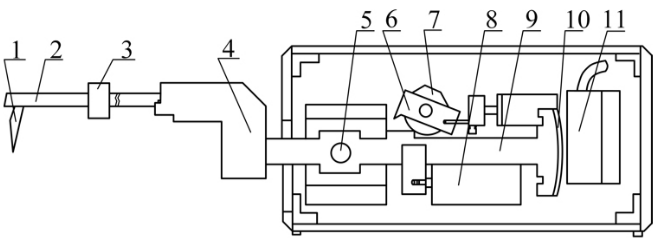

Fig. (3a). Device structure [43].
1. connected stylus, 2. stylus rod, 3. adjustment weights, 4. stylus holder, 5. rotary axis, 6. stylus holder, 7. stylus lifting mechanism, 8. dampers, 9. sensor levers, 10. scale, 11. scale read-heads.

For the stylus displacement sensor, the magnitude of the measuring force between the stylus and the sample to be measured directly affects the quality of the microstructure topography detection. If the measuring force is too large, it will lead to deformation of the tip of the stylus and the measured surface, which will affect the measurement accuracy and damage the stylus and the measured surface; if the measuring force is too small, it will not ensure good contact between the stylus and the sample, and it is easy for the stylus to jump, stick-slip and destabilization phenomena, which will affect the final detection results. Therefore, samples should control different measurement forces for different materials to be measured to ensure the best measurement results. The traditional methods of controlling the measuring force mainly include gravity control and elasticity control. The former applies gravity to the stylus and its connecting components to generate the measurement force. At the same time, the latter connects the stylus with the elastic element and utilizes the elasticity of the elastic element to generate the measurement force. Both methods have certain disadvantages: the measuring force of gravity control is fixed. It cannot be changed flexibly according to the material of the measuring surface, and the measuring force of elasticity control changes with the morphology of the sample surface, which cannot always be maintained stably and may cause damage to the sample in some cases.

H. Fang, B. Xu, D.Q. Yin and Q.Q. Liu [73] of Sichuan University presently invented a stylus-type displacement sensor with controllable measuring force for microform detection. This sensor utilizes a magnetically levitated bearing and an electromagnet to achieve precise control of the measurement force.

This solution uses a combination of magnetic levitation bearings and electromagnets to control the measuring force precisely. When measuring, the probe can follow the changes in the surface of the sample to be measured and moved, and then the displacement detection module measures the probe's displacement information.

When the probe moves with the surface of the sample, the gap between the electromagnet and armature changes, resulting in changes in the electromagnetic force; the current of the electromagnet can be adjusted so that the measuring force can be precisely controlled. The measuring force can be stabilized by adjusting the electromagnet current. This will control the measuring force in a certain precise range by adjusting the electromagnetic force, which can ensure good contact between the probe and the sample without damaging the sample and improve the measuring accuracy of the stylus displacement sensor. Completely changing the traditional stylus displacement sensor in the measurement force is not measurable, and it is not easy to control the technical defects [45, 73]. The specific device is shown in Fig. (**3b**).

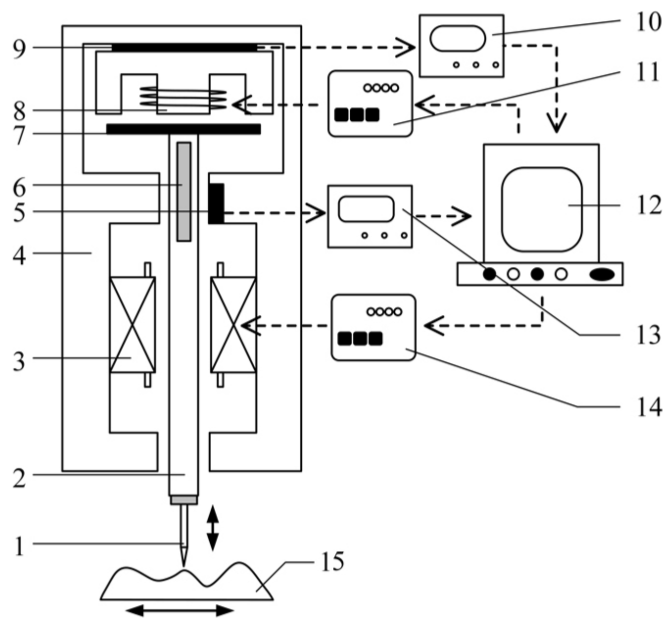

Fig. (3b). A stylus displacement sensor with controllable measuring force for microform detection [73].
1. probe, 2. probe rod, 3. non-contact bearing, 4. sensor base, 5. reading head, 6. grating scale, 7. armature, 8. electromagnet, 9. microtensile pressure sensor, 10. signal acquisition module, 11. coil control module, 12. signal analysis and processing module, 13. displacement signal acquisition module, 14. bearing control module 15. sample to be measured.

A magnetically levitated stylus displacement sensor has been invented by S.P. Chang, H. Wu, C.B. Hu, J.F. Zhou *et al.* [4] at Huazhong University of Science and Technology. The device levitates the stylus shaft by setting a ring magnet and a pair of levitation coils, and it maintains its position using two guiding modules and four magnetic poles. A gap sensor above the magnetic poles detects the deflection of the stylus shaft in real time and feeds it back to the input, where the size of the electromagnetic field is adjusted by changing the current size to ensure that the stylus shaft is always in the centre position.

This device measures force control by adjusting the size of the current in the suspension coil to realize, both to ensure that the stylus and the measured surface contact but also to prevent the stylus from scratching the measured surface. In particular, the device stylus uses a cone angle of 90° radius of 2 μm needle tip probe; the benefits of this stylus are, on the one hand, it can prevent the stylus words damage to the measured surface, on the other hand, it can be filtered out some of the low-frequency information, which can be for the convenience of the subsequent data processing.

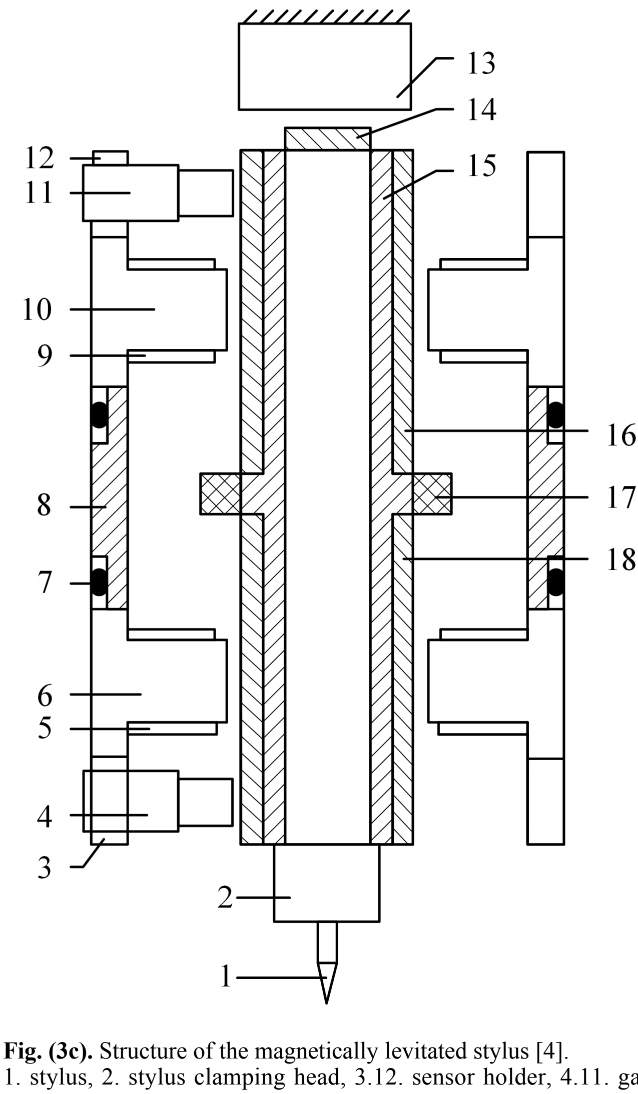

Fig. (3c). Structure of the magnetically levitated stylus [4].
1. stylus, 2. stylus clamping head, 3.12. sensor holder, 4.11. gap sensor, 5.9. current-carrying coil, 6.10. magnetically levitated bearing, 7. levitation coil, 8. coil cage, 13. optical metrology module, 14. reflector, 15. stylus shaft, 16.18. square bushing, 17. ring magnet.

When the measurement is carried out, the white light interference principle is used. When the displacement of the stylus axis in the vertical direction changes, the interference fringes also move, which is received by the four-quadrant photodetector and sent to the computer for processing. The small displacement of the measured object in the vertical direction is measured by detecting the change of the interference fringes. The measurement module adopts laser interferometric measurement, and the angular cone prism is insensitive to angular deflection, which provides easy installation and high stability.

The main feature of this patent is based on the unique magnetic levitation support technology, which ensures that the stylus axis is always in a vertical position during the measurement process. The contact force between the stylus and the tested part is kept constant and measured in the vertical direction, which has the advantages of simple structure, ease of operation, high measurement accuracy, high positioning accuracy, controllable measurement force, and good stability of the movement, *etc.* [10, 13]. The structure of the device is shown in Fig. (**3c**).

This patent is based on magnetic levitation support technology, the use of electromagnetic force levitation up the stylus axis, the two ends of the magnetic bearing to ensure that the stylus axis in the measurement process is in a vertical position, the stylus and the test piece of the contact force to maintain a constant, and in the vertical direction of the measurement, is easy to operate, has a simple structure, high precision measurement, high positioning accuracy, controllable measurement force, good stability of movement and other advantages [4, 74]. The structure of the device is shown in Fig. (**3c**).

A multi-mode atomic force probe scanning system has been disclosed by Y.H. Li, D.S. Wang, Q.X. Li *et al.* [9] from Tsinghua University. The device belongs to the field of nano-surface inspection technology, in which the surface to be inspected is placed on a scanning table driven by a servo control unit, and a solid microcantilever probe is used for inspection, with a piezoelectric double wafer on the fine-tuning mechanism, and the piezoelectric double wafer is connected to the end of the microcantilever probe. The transverse resolution can reach the nanometer level, and the axial deflection of the microcantilever probe is detected by a low-frequency differential dual-frequency laser interferometer so that the longitudinal resolution can reach the angstrom level accuracy. On the other hand, using large-range scanning tables and image stitching and recognition technology greatly improves the detection range, which can realize the surface inspection of the whole disc, disk, or wafer. In the working process, the white light interference principle is utilized to obtain the axial deflection of the micro-cantilever probe by detecting the optical range difference between the measurement light and the reference light. The device can choose one of the three modes of microcantilever contact, non-contact, or tap mode for detection according to the different measurement requirements. In addition, due to the horizontal structure of the device, it effectively avoids the influence of the self-gravity of the microcantilever probe on the atomic force. Ultimately, it realizes the precision detection of a large field of view, nanoscale ultra-precise surfaces, as well as the surfaces of conductors [9], semiconductors and insulators. The device is shown in Fig. (**3d**).

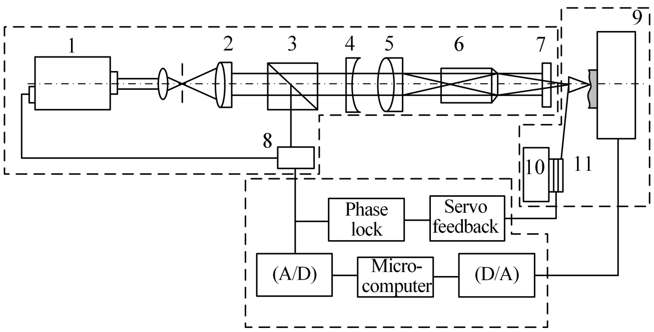

Fig. (3d). Multi-mode atomic force probe scanning system [9].
1. transverse seiman laser, 2. double glued lens, 3. beam splitter, 4. negative lens, 5. birefringent lens, 6. infinite barrel length microscope objective, 7. reference mirror, 8. photodetector, 9. scanning stage, 10. fine tuning mechanism, 11. piezoelectric double chip

4. INTRODUCTION OF PATENTS FOR NON-CONTACT SURFACE INSPECTION

Non-contact measurement methods mainly refer to optical measurement represented by the probe not being in contact with the surface to be measured [57]. This type of measurement device is usually more complex, and the working conditions are higher, but at the same time, the detection accuracy is also higher, and it will not damage the surface to be measured.

F.G. Yang, M. Li, W.F. Sheng and P. Liu [75] from the Institute of High Energy Physics, Chinese Academy of Sciences, invented a surface shape detection device and detection method. This is a new type of surface shape inspection equipment developed to meet the needs of large-range surface shape measurement on a two-dimensional scale. The structure of the device is shown in Fig. (**4a**).

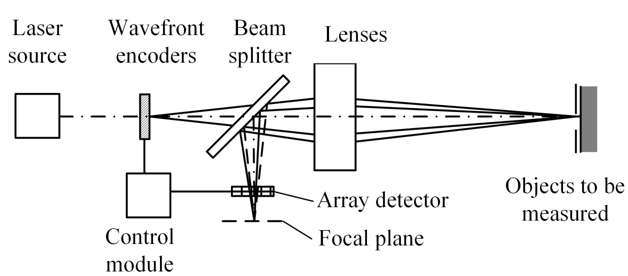

Fig. (4a). Structure of the face shape detection device [75].

The device uses a light source modulated and encoded by a wavefront encoder to produce a spot on the surface to be measured and the detector through the detection optical path. By controlling the wavefront encoder, the light spot on the surface to be measured can be driven to move, and the tilt angle of the surface to be measured can be obtained by comparing the collected signal with the reference light spot and then the surface profile of the surface to be measured can be deduced. Specifically, the light reflected from the surface to be measured is ultimately imaged on a focal plane of the lens, and the array detector is located on an out-of-focus surface between the lens and the focal plane. The closer the array detector to the lens, the higher the precision of the measurement, while the image range of the light spot recorded by the array detector is small; conversely, the precision of the measurement becomes lower and the image range of the light spot recorded by the array detector becomes larger. This enables fast switching between the two measurement modes, high precision-small range mode and low precision-large range mode. Fig. (**4b**) shows the block diagram of the control module.

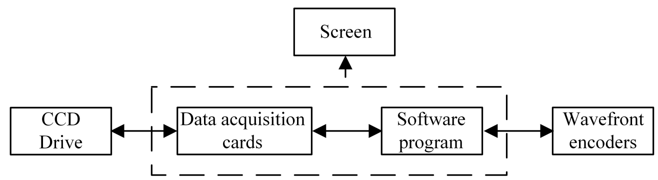

Fig. (4b). Block diagram of control module structure [75].

This detection method solves the problem of large-range surface shape measurement in a two-dimensional scale and is able to realize rapid switching between the two measurement modes of high-precision-small-range mode and low--precision-large-range mode; it is suitable for the measurement of two-dimensional objects, especially for on-line detection of the optical components mounted on the synchrotron radiation beamline [75].

Q. Fan, H.R. Yang, and G.P. Li [68] of the 205th Research Institute of China's Armaments Industry disclosed a facing accuracy detection device for aspheric optical elements. The device provides an aspheric optical element facing accuracy detection device based on two-step phase shift technology, computational holography technology and digital holographic interference technology on the basis of the existing interferometric detection in order to realize high-precision detection of the facing accuracy of the aspheric optical element with a large asphericity and a large face shape steepness. Specifically, the present invention is built based on the existing interferometric surface shape detection device and cleverly realizes the light intensity measurement of the detecting light wave and the reference light wave by adding two controllable diaphragms. The laser beam from the HeNe laser is divided into two beams by the beam splitter after the filter, forming the detection and reference light waves, respectively. When the first and second controllable diaphragms are opened at the same time, the CCD detector detects the interference fringes, and when only the first controllable diaphragm is opened, the CCD detector detects the reference light wave or the light intensity of the detection light wave; the acquisition of interference fringes of different phases is realized by the piezoelectric ceramics generating a phase shift. Through this information, the phase deviation between the surface shape to be measured and the simulated ideal surface shape wrapped between 0 and 2π can be calculated, a set of continuously changing phase difference values can be calculated after unwrapping, and the deviation between the surface shape to be measured and the simulated ideal surface shape can be obtained by calculating and solving. The specific device is shown in Fig. (**4c**).

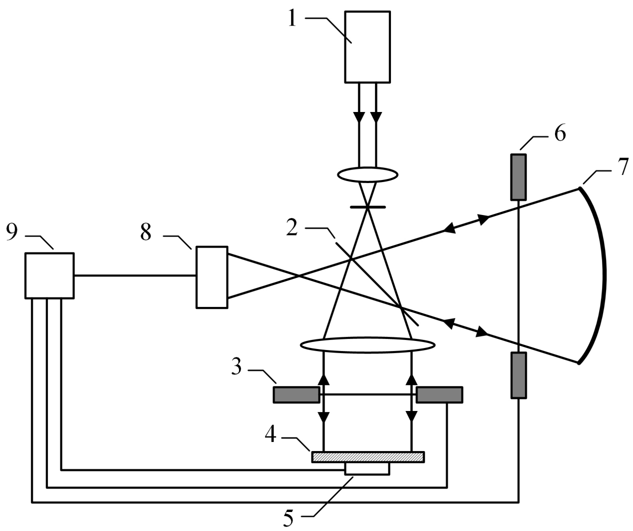

Fig. (4c). Schematic diagram of the face shape detection device for aspheric optical elements [68].
1. helium-neon laser, 2. beam splitter, 3. 6. controllable diaphragm, 4.8. CCD, 5. piezoelectric ceramics, 7. aspheric samples to be measured, 9. computer.

The advantage of this detection method is that it overcomes the problem of the existing computational holography technique for detecting the face shape of aspheric optical elements, which is difficult to process and adjust the computational hologram and realizes the quantitative detection of the face shape of large aspheric degree aspheric optical elements, which doesn't need to process the computational hologram, and reduces the cost of detection and shortens the detection period. The difference between the face shape of the aspheric optical element to be inspected and its ideal face shape can be effectively reduced by the method of direct comparison. The method of the difference between the face shape can effectively reduce the amount of deviation generated in the detection process, and the phase deviation between the face shape of the aspheric optical element to be inspected and its ideal face shape can be obtained more conveniently and the detection accuracy is improved [68].

Gohjun Ando and Jue Sakai [13] invented a surface inspection device and a surface inspection method. The device is an inspection device that detects the surface topography of a material based on the intensity of light reflected from the surface and is mainly used for detecting depressions and protrusions on the optical plane on the order of a few micrometers. The device is shown in Fig. (**4d**-**f**).

The detection principle is shown in Fig. (**4**-**5**); the light emitted by the light source is irradiated to the surface to be tested at a certain angle, the light emitted by the light source is modulated, and its intensity distribution is higher the closer to the surface light intensity. If the surface is flat, the light should be reflected from the surface mirror at the same angle to reach the CCD camera fixed in a certain position and be detected. However, if there is a bump on the surface, high--intensity light directed at the surface at a low angle will reach the CCD camera and be detected. Conversely, if there is an indentation on the surface, high-intensity light directed to the surface at a higher angle reaches the CCD camera and is detected.

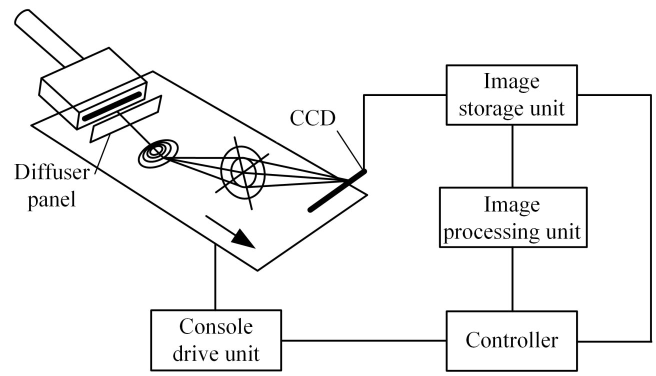

Fig. (4d). Schematic diagram of surface inspection device [13].

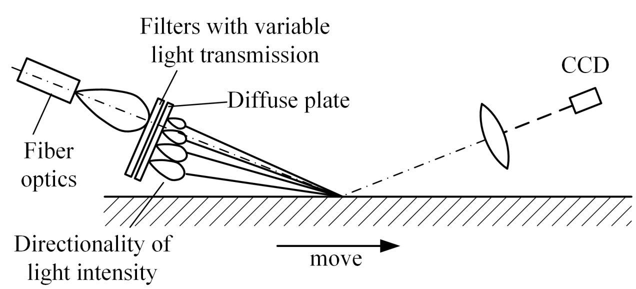

Fig. (4e). Principle of detection device [13].

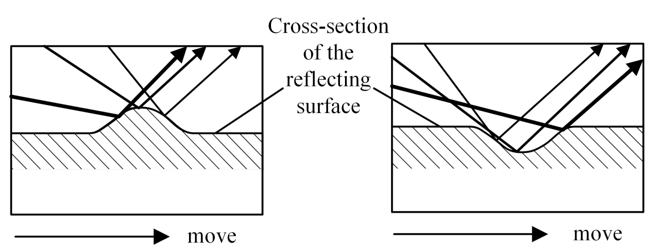

Fig. (4f). Surface Reflection Schematic [13].

Specifically as shown in Fig. (**4f**) represents the reflection cross-section when there is a bump on the surface; the beam is irradiated while the surface to be tested moves to the right; at this time, compared with the flat surface, the light is reflected to the upper part of the surface, and the high-intensity light irradiated at a low angle reaches the CCD camera and is detected. If there is a depression on the surface, the light is reflected further down, as shown in Fig. (**4f**). Therefore, the light intensity detected in the CCD sensor can be used to determine whether the surface to be measured is flat or not, as well as if there are defects and the details of the defects' projections or depressions [13].

H.Z. Zhao, H. Fu, M.Y. Fan, R.R. Niu, *et al.* from Hefei University of Technology [30] have disclosed a displacement sensor based on coaxial laser triangulation and microscopic imaging and its application. This device is a displacement sensor based on the laser triangulation principle and microscopic imaging method, which can realize high-precision real-time online measurement of displacement. In particular, this device has two sets of measurement optical path systematic diagrams, which are set up with coaxial reversal of the microscopic objective lenses, which can be used to determine the parameters of the surface of the inner pore type. The accuracy of this sensor is as high as the nanometer level, which can realize the high precision measurement of surface parameters such as component surface, inner diameter, plane pitch, *etc*. It has the characteristics of a simple structure, and its price is much lower than other that of instruments and equipment with the same accuracy, which saves the measurement cost to a large extent [30].

Hisayasu Morino and Jun Takashima [76] disclosed a confocal sensor with a larger measuring range. In this device, it is possible to continuously change the measurement range by continuously changing the distance from the pinhole to the diffractive lens, thereby continuously measuring the distance to an object over a larger range. It is also possible to replace a variety of holders that hold the diffractive lens in different positions. By replacing various holders, the measurement range can be changed in stages [76-78]. An overview of the confocal sensor is shown in Fig. (**4g**).

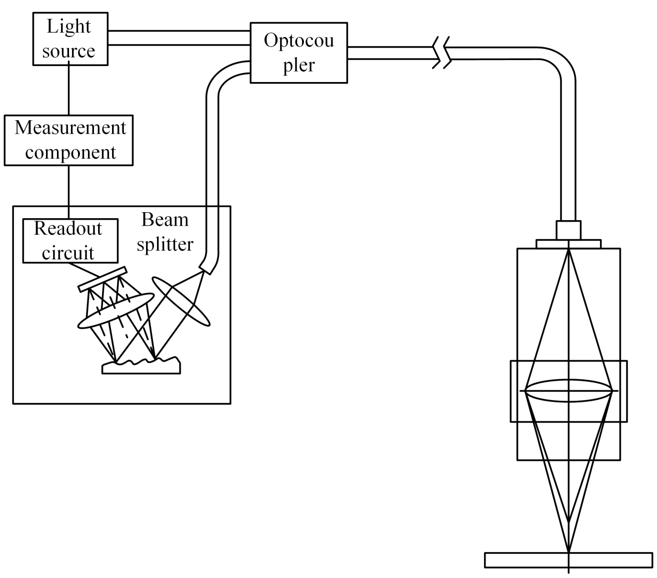

Fig. (4g). Outline diagram of confocal sensors [76]

D.M. Gao, X.Y. Zhang [79] invented a three-dimensional surface shape detection method and device. The device uses a phase deflection measurement technique to measure the specifics of the surface to be measured using modulated streak light. The device comprises a camera set, a material placing platform and a projection device. The camera set comprises a main detection camera and an auxiliary positioning camera for detecting whether or not the currently projected stripe pattern of said projection device is projected.

The projection device projects a stripe pattern to the measured object when measuring. It monitors the projection process and switches to the next stripe pattern after the current stripe pattern projection is completed. The three-dimensional profile shape of the measured object can be solved based on the projection information reflected from the measured object. The projection device is monitored during the projection process so that the next pattern is switched immediately after it completes the current stripe pattern projection to improve the overall detection efficiency [79, 80]. The device is shown in Fig. (**4h**).

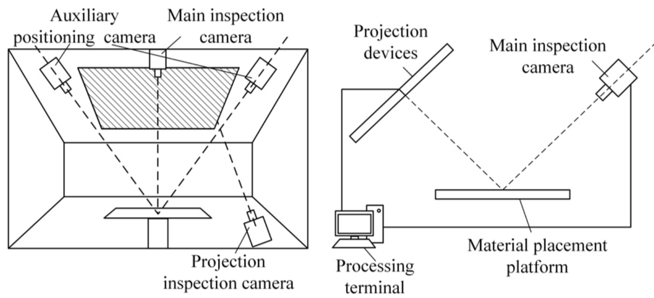

Fig. (4h). Three-dimensional face shape detection device [79].

The accuracy of the stripe projection technique can only reach the micrometer level, while the phase deflection measurement technique can reach The accuracy of the stripe projection technique can only reach the micrometer level, while the phase deflection measurement technique can reach micrometer to nanometer level accuracy, which can be compared with the accuracy of the interferometer. The main advantages of this method based on the phase deflection measurement technique are that it requires fewer auxiliary components during the measurement process and has a large dynamic measurement range. With the appropriate algorithms, the detection efficiency can be very high, which is suitable for the inspection of large quantities, simple shapes and low-steepness surfaces [81-84] (Fig. (**4i**-**j**).

J.J. Dong, Y. Zhong [64] *et al.* of Hefei University of Technology disclosed a flatness detection pneumatic probe, the differential pressure gas circuit includes a gas source, a filter, an inlet valve, a regulator, a pressure gauge, a pneumatic probe and a computer and a sensor.

Compressed air output from the gas source, after the filter pressure stabilizer, becomes a relatively pure, dry gas, gas all the way through the main nozzle I into the differential pressure sensor high-end air pressure input, all the way into the main nozzle of the pneumatic probe II, through the measurement of the nozzle and the gap between the workpiece to be measured into the atmosphere, the main nozzle II and the main nozzle I device with the same aperture. Currently, the pressure in the gas chamber is the back pressure. The back pressure is sent to the low-end input of the differential pressure sensor through the pressure port, and the differential pressure sensor measures the differential pressure between the two. Multiple probes can measure the differential pressure value at multiple points on the plane through multiple sensors, and the differential pressure sensor converts the differential pressure value into a voltage value, which is captured by the data acquisition card and then sent to the computer for data processing to obtain the flatness error [64]. Figures 4i and 4j show the device's pneumatic probe structure and the gas differential pressure circuit.

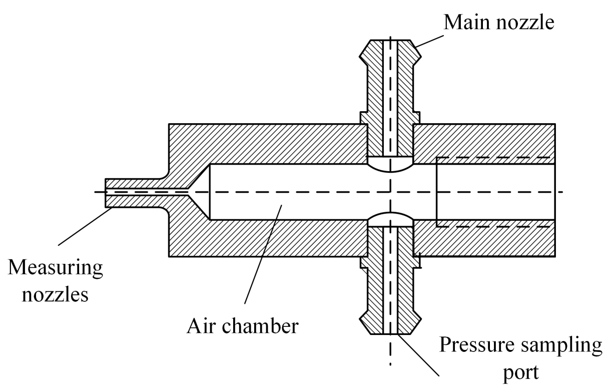

Fig. (4i). Pneumatic probe structure [64].

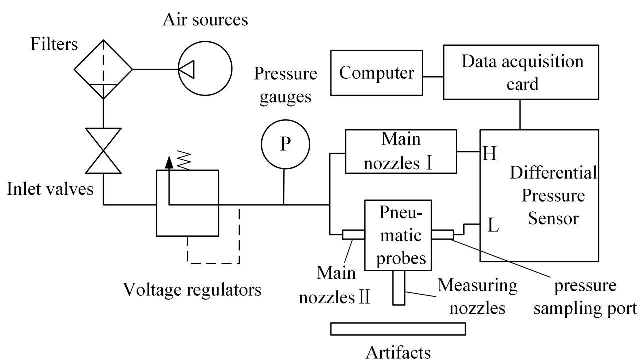

Fig. (4j). Differential Pressure Air Path for Pneumatic Side Heads [49].

The pneumatic probe realizes the conversion of dimensional quantity - pneumatic pressure quantity, which has the characteristics of high measurement accuracy and good stability and can be used in industrial production. The design method has some generality and reference significance for the design of probes for different measurement applications in pneumatic measurement.

5. INTRODUCTION OF PATENT FOR DETECTION DEVICE

Choosing the right optical mold inspection method is, of course, very important. However, an excellent inspection platform can be accurate measurement and evaluation of the surface accuracy of the mold [85] to ensure that the processing accuracy and geometry of the mold are in line with the design requirements, greatly improve the detection efficiency, reduce the detection error and timely analysis of the inspection data, to ensure the quality of the mold, improve production efficiency, reduce production costs are of great significance [86-88].

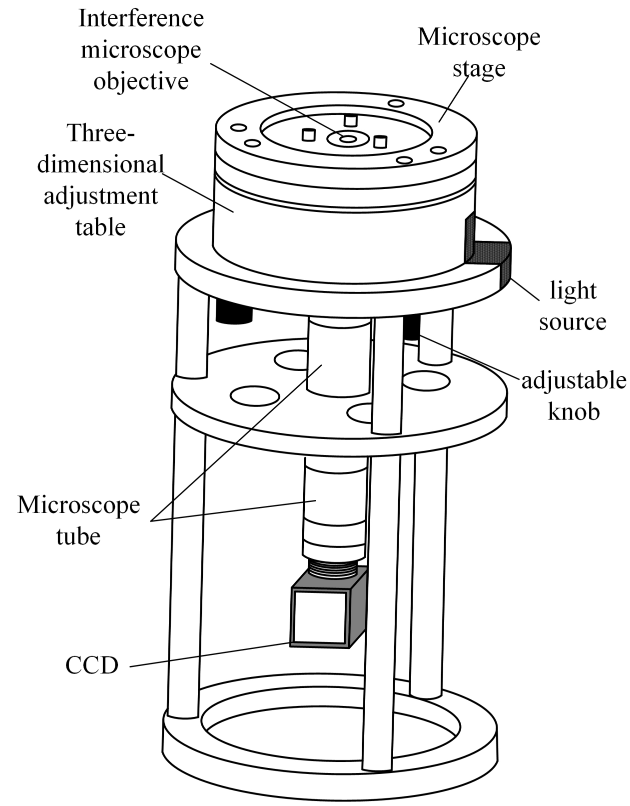

Fig. (5a). High-precision portable optical surface three-dimensional shape online detector [89].

L. Chen, D.H. Zheng, Y. Zhang, W.H. Zhu *et al.* [89] from Nanjing University of Science and Technology have disclosed a high-precision portable online tester for the three--dimensional topography of optical surfaces. The device adopts an embedded structure, in which a monocular interference microscope is embedded in a mechanical support, and all of its optical paths are encapsulated in the microscope tube, which improves the integration of the optical paths as much as possible, and greatly reduces the volume and weight of the instrument to achieve portability. The top of the stand uses a three-point positioning structure of the ring-shaped three-dimensional adjustment stage, relying on the three adjustable knobs to achieve high-precision tilt and longitudinal displacement adjustment of the entire adjustment stage. A Coaxial illumination system is used in the optical structure; the light beam from the light source is reflected into the objective lens through the trans-reflector, and then converged and interfered with by the beam splitter after reflecting from the reference mirror and the surface of the mirror under test, respectively. The reference mirror is along the direction of the optical axis to do displacement movement. At the same time, the detector records the interference field at each point of the light intensity value through the calculation of the three-dimensional shape of the surface to be measured [89]. The device is shown in Fig. (**5a**).

The advantages of this device are small size, good vibration resistance, can meet the optical, microelectronics, machinery and other fields of ultra-precision machining components of high-precision online rapid batch testing, can be applied to the chip, LED, micro-mechanics, micro-optics, aerospace optical gyroscope, strong laser, astronomy telescope and other production and scientific research fields.

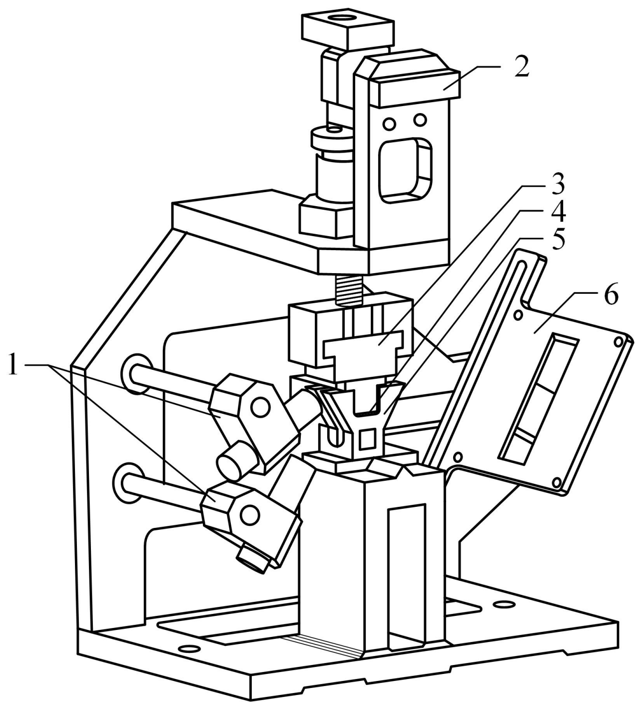

Fig. (5b). Optical surface plasmon resonance biosensor measurement device [15].
1. laser carrier, 2. adjusting handle, 3. platen, 4. au membrane prism, 5. prism bracket, 6. ccd bracket.

J.D. Hu, Y. Chen, F.J. Hu, W.S. Wei, H.Q. Li [15, 16], of Henan Agricultural University disclosed an optical surface plasmon resonance biosensor measurement device as shown in Fig. (**5b**). It comprises a biochip assembly adjustment unit, a laser adjustment unit, a CCD adjustment unit, a support plate and a base on which the support plate is mounted. The laser adjustment unit comprises two sets of laser carrier frames and corresponding carrier spindles, each laser carrier frame being mounted on one end of its corresponding carrier spindle, and the other end of the carrier spindle being fixedly mounted on a support plate. The laser adjustment unit and the CCD adjustment unit are symmetrically distributed on both sides of the prism carrier, and the positional relationship between them can be adjusted so as to form a corresponding optical channel between the two sets of lasers, the biochip assembly and the CCD. The adjustment mechanism has a wide detection range, high testing accuracy, and stable and reliable testing performance [15] (Fig. **5b**).

Q.S. Li, R.D. Wang, H. Zhang *et al.* [90] of Changchun Institute of Optical Precision Machinery and Physics, Chinese Academy of Sciences, invented a face shape detection device for aspheric optical elements, which utilizes an interferometric method to realize the measurement of the measured face of aspheric optical elements in the vertical downward direction, thus reducing the influence of the support method and the direction of gravity in the measurement of the other directions on the detection accuracy, and improving the accuracy of the face shape detection of aspheric optical elements.

CONCLUSION

The patents studied in this paper involve various optical mold surface inspection methods; a review of these patents' literature found that the most widely used methods are the stylus method, white light interference method, laser triangulation method and geometric light method. Various optical mold surface inspection methods have advantages and limitations, and the appropriate method must be chosen according to the specific application requirements and inspection objects. Due to the presence of measuring force, there is a risk of scratching the surface of the workpiece, while on the curved surface, the measurement of lateral force on the measurement accuracy will have an impact. However, the measurement data is reliable and environmentally adaptable. Non-contact measurement methods, such as the optical probe method, avoid the contact probe due to the presence of measuring force problems, but the data is susceptible to the surface roughness of the workpiece and the environment and other factors. Therefore, developing high-resolution, small measuring force of the contact probe, *i.e.* micro-force contact measurement technology and high-precision optical probe inspection technology, has become a current research hotspot.

Another noteworthy point is that automation and intelligence are important directions for the future development of optical mold external surface inspection methods. With the progress of science and technology, automation and intelligent technology have been widely used in optical mold external surface inspection. For example, the use of machine vision and artificial intelligence technology can realize the automatic identification and classification of defects on the surface of the mold, thus improving detection efficiency and accuracy. Data analysis and iterative algorithm optimization can extract effective features of mold surface defects and accurately assess their severity through reasonable data processing and analysis methods. In addition, continuous optimization of the algorithm to improve the accuracy and robustness of the model is also one of the directions for future research on optical mold external surface inspection methods [20, 89, 91-99].

CURRENT AND FUTURE DEVELOPMENTS

The current optical mold external surface inspection methods have made significant progress. The introduction of new technologies, such as high-resolution imaging technology, digital image processing and recognition technology, AI intelligent analysis technology, *etc.,* has greatly contributed to the progress of the optical mold external surface inspection methods [9] and its detection accuracy and detection efficiency have been greatly improved.

It has been possible to accurately detect tiny defects on optical surfaces or complex-shaped surfaces and provide fine surface topology information. Not only that, but the application scope of these inspection methods is expanding. In addition to the traditional optical component manufacturing field, optical mold surface inspection methods are also used in other industries, such as electronics, automotive, aerospace, *etc*. These industries are increasingly demanding high precision and quality mold surfaces, and therefore, the need for research and improvement of inspection methods is becoming more urgent.

With the development of technology, microstructured optical functional elements in the aerospace, mechatronics, optics and optoelectronics fields have very important application value and extremely broad application prospects, for which the molds for large-volume reproduction are also receiving more and more attention. The surface accuracy of the mold is decisive for the function of the microstructure optical functional elements; the current ultra-precision surface processing technology has gradually matured, and the surface inspection technology has become a technical bottleneck. Suppose the surface inspection technology makes a breakthrough. In that case, whether in the field of photoelectric imaging, fiber optic communication, information processing, biomedicine, automotive lighting, laser machining and other civil industries or in the field of modern national defense science and technology, microstructured optical components will show an important application value and broad application prospects [100, 101].

The combination of traditional inspection methods and new technologies in the future will also be the direction of optical mold external surface inspection methods; with the continuous improvement of new technologies, optical mold external surface inspection methods may tend to develop into three-dimensional surface inspection technology to more comprehensively capture the surface morphology and microscopic defects, and to improve the detection accuracy. With the deep combination of big data analysis and artificial intelligence technology, the inspection methods will be more intelligent, constantly optimize the inspection algorithm, and develop in the direction of real-time monitoring and predictive maintenance to help the manufacturing industry carry out equipment condition monitoring and preventive maintenance [102-104].

Overall, optical mold surface inspection methods in various fields have emerged in various inspection methods and technologies; these methods have their characteristics and are suitable for different types and requirements of mold surface defect detection. However, in the face of requirements such as complex shapes of mold surface inspection and high--throughput inspection in mass production environments, there are still many shortcomings in the current inspection methods. Therefore, future research and development should focus on solving these challenges and proposing more efficient, accurate and intelligent methods for optical mold surface inspection.

AUTHOR'S CONTRIBUTIONS

G.L. and J.L. contributed to the research design and implementation, as well as the data analysis and manuscript writing.

ABBREVIATIONS

CCD	=	Charge Coupled Device
STM	=	Scanning Tunneling Microscope

CONSENT FOR PUBLICATION

Not applicable.

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CONFLICT OF INTEREST

The authors declare no conflict of interest, financial or otherwise.

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