Defect detection for highly reflective rotary surfaces: an overview

Awei Zhou, Bobo Ai, Pingge Qu and Wei Shao

1 College of Mechanical and Electronic Engineering, the Xi’an Key Laboratory for Modern Intelligent Textile Equipment, Xi’an Polytechnic University, Xi’an 710048, People’s Republic of China
2 College of Mechanical and Precision Instrument Engineering, Xi’an University of Technology, Xi’an 710048, People’s Republic of China

E-mail: lxmwsawz@163.com

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Abstract
Defects over a highly reflective rotary surface (HRRS) may change the service performance, lifespan and safety properties of products. Therefore, defect detection is very important for surface quality assurance. In this paper, the attributes of HRRS defect detection are described. Then, a comparative overview in terms of key parameters in the HRRS defect detection systems is elaborated. Finally, this paper reviews various detection technologies for HRRS defect detection and categorizes the previous literature by their detection technologies, which can provide a reference for further implementation and improvements in this field. This study provides guidelines for selecting which scheme is the most suitable when designing new HRRS defect detection systems.

Keywords: HRRS, defect detection, detection attributes, detection parameters, comparative studies

(Some figures may appear in colour only in the online journal)

1. Introduction

A highly reflective rotary surface (HRRS) refers to the surface of smooth and precise rotating parts with extremely strong reflective properties, almost as reflective as a mirror, and a clear reflection of the image of the article. Precise rotating parts such as aviation bearing steel balls, precision steel balls and precision cylinders have HRRSs and are widely used in aviation, aerospace, railways, precision machine tools, automobiles and other fields.

With the development of downstream industries such as aviation, aerospace, railways, precision machine tools and automobiles, the demand for high-end precision rotary parts will greatly increase. For example, the global market for railway technology is seeing a stronger growth, with a current market volume of EUR 183 billion and an expected annual growth rate of 2.8% [1]. In the study ‘Worldwide Market for Railway Industries’, which was published for the InnoTrans 2018 trade fair, the annual growth rate has increased from 1.3% (2016) to 2.4% [1]. The market study ‘Light Rail Vehicles—Global Market Trends 2019’, published by SCI Verkehr [2], reported that light rail vehicles are trending worldwide: 8% annual growth expected for new procurements until 2023. These growths will bring good market prospects.

However, during the production and post-processing processes of such parts, surface defects such as pits, scratches, abrasions, etc, affect the product’s performance, accuracy and life, and can even cause serious accidents and significant economic losses [3, 4]. Specifically, as an important part of the bearing, the quality of the steel ball is directly related to...
bearing accuracy, dynamic performance and service life; its importance is second only to the bearing inner ring [5]. Many experiments show that the percentage of the impact factor of the surface defects of the steel ball on bearing noise is about 70% [6, 7], and the ratio of bearing failure caused by the surface defects of the steel ball is above 58.8% [8, 9], which objectively describes the status and importance of steel balls in the bearing industry. Due to different processing technologies, defects may appear on the surface during the manufacturing process of the steel ball, which will lead to increased friction and vibration of the bearing. If no measures are taken, the machine will fail. Furthermore, defect detection of such ‘HRRSs’ is one of the most challenging research fields. Therefore, recently, researchers have started focusing on developing reliable detection techniques for HRRS defects. To the authors’ knowledge, there are currently no papers that focus on reviewing the existing detection techniques for HRRS defects except one published by Zhou et al [10]. In [10], the author provides a brief overview of recently published papers about traditional HRRS defect detection methods and does not compare the various methods. However, this paper describes the features of defect detection in HRRSs by focusing on their surface reflective properties and detection interference caused by surface curvatures and their detection environment. Then, the key parameters in HRRS defect detection systems (DDSs) are discussed. Finally, this paper provides a comprehensive overview of the existing detection techniques used for dealing with defect detection in HRRSs. These detection techniques are classified into four major categories: manual methods, non-vision-based methods, vision-based methods and hybrid methods. Vision-based methods are classified into three major categories: detecting environmental constraint (DEC) methods, special lighting (SL)-based methods and other methods. In addition, the essential features of these different HRRS defect detection methods are compared. Figure 1 displays the overall structure of the paper, with related studies in each node.

This paper is organized as follows: section 2 introduces the features of defect detection for HRRSs. Section 3 describes the key parameters in HRRS DDSs. Section 4 describes the different existing defect detection methods for HRRSs in detail. Finally, a conclusion and outlook are given in section 5.

2. Features of HRRS defect detection

Detection of HRRS defects defines the detection processes that are used in the field of production technology for surface defect detection of objects with extremely strong, almost specular, reflective properties. Additional attributes of HRRS defect detection are:

(a) Because the highly reflective surface is close to specular reflection, it is easy to cause surface glare and local saturation distortion of the collected image brightness, which makes the defect information to be detected easily submerged.

(b) The non-negligible influence of reflecting surrounding scenes on the measured parts.

(c) Parts with different surface curvatures and relatively high curvatures are difficult to measure.

(d) There may be multiple types and sizes of defects in the same area.

(e) In many cases, defect detection is carried out in an industrial environment. However, factors such as noise and ambient light in the industrial environment have a large influence on the detection process.

3. Key parameters in HRRS DDSs

3.1. Types of sensors

Two kinds of sensors are principally used in HRRS DDSs:

(a) Single sensors: This kind of sensor is used to sense real information about HRRS defects. In HRRS DDSs, various single sensors have been used such as fiber optic sensors [11–13], an ultrasonic probe [14], capacitance sensors...
3.2. Curvature radius of the measured surface

The curvature radius of the measured surface is one of the key factors influencing the performance of HRRS DDSs. Figure 2 shows an original picture of grid paper attached to the surface of a cone (i.e. the radius of curvature is a certain value). It is obvious that the grid has geometric deformation. However, there will be no geometric deformation of the grid when the grid paper is attached to a plane surface (i.e. the curvature radius is infinite). It can be seen that the imaging results of the measured surface with different curvature radii are different and the influence on the detection process (such as the relative aperture of the detection area, the size of the probe, the detection distance, etc) and the subsequent processing (especially the image mosaic) are also different.

Specifically, when detecting surface defects with a certain curvature radius $R$ ($R \neq 0$ or $\infty$), if the detection area is larger than the aperture (or probe) or the detection distance is smaller, the larger the data volume is, the stronger the noise suppression effect is and the higher the detection accuracy is, but the time to complete the detection is longer. However, when the relative aperture of the detection area increases, the relative repeatability standard deviation of the detection results and the measurement efficiency decreases. When the relative aperture is larger than a certain value, increasing the relative aperture has no obvious effect on improving the detection repeatability. Moreover, because reducing the detection distance will lead to a decrease in detection efficiency, and the long detection time will make the instrument drift and lead to detection error, so the detection distance cannot be infinitely reduced. Therefore, in practical applications, the appropriate detection area, relative aperture (or probe) size and detection spacing should be selected according to the measured parts with different curvature radii $R$.

3.3. Complete detection of the entire HRRS without dead zones

HRRSs are required to be inspected throughout their entire surface without dead zones. For that purpose, various techniques have been developed such as two-dimensional motion (TDM)- and one-dimensional motion (ODM)-based expansion methods.

3.3.1. TDM-based expansion method.

The meridian based TDM deployment method was originally used in eddy current (EC) flaw detection, such as the AVIKO steel ball surface quality tester produced by Czech SOMET company. In this TDM expansion method, driven by the unrolling wheel and the driving wheel, the steel ball rotates around a variable axis and the sensor continuously collects data, thereby realizing the unfolding of the steel ball surface [40]. However, this method requires that the contact between the driving wheel, the unrolling wheel and the steel ball are rigid, and the unrolling wheel is prone to wear and the maintenance cost is high.

Pan et al [41] designed a steel ball surface unfolding stage based on the meridian unfolding principle, which was used to evaluate the quality of the steel ball surface. In this study, the authors directly replaced the unrolling wheels with V-shaped grooves with unequal gradients on both sides and replaced the driving wheels with driving sticks to achieve the surface expansion of the steel balls. Wang et al [42] developed a TDM expansion method based on latitude and longitude scanning, that is, when the steel ball rotates along its meridian direction, the sensor swings along the equatorial direction of the steel ball to achieve the surface expansion of the steel ball. The steel ball defect detector was developed by Wang et al [43] and Zhao et al [44]. The steel ball enters the detection cavity through the feeding system, and the friction disk at the bottom of the steel ball makes periodic rotation and intermittent translation. At the same time, the feed disk drives the steel ball to rotate at a certain speed, so that the surface of the steel ball can be unfolded.

From the above-reviewed literature, the current TDM-based expansion method (which ensures that the entire surface of the steel ball is detected during the detection process) is theoretically probabilistic, cannot guarantee that the entire surface can be completely detected, the results are low in reliability and stability, and the unfolding mechanism is complex, huge and easy to wear.

3.3.2. ODM-based expansion method.

Wang et al proposed a dual charge coupled device (CCD)-based sphere surface expansion method [45]. This method uses a dual CCD camera to continuously acquire images during the rolling process of the sphere (the ball relies on gravity to perform one-dimensional movement along the track) to achieve full expansion of the sphere surface. Experiments verified the effectiveness of this method. Shao et al proposed a method for unfolding the surface of a cylinder based on a high-precision turntable [31]. In this study, the authors placed the inspected
parts directly on a high-precision turntable. At each angle of the turntable, a single vision sensor collected images of the rotating surface, and so on. Then, according to the method of image stitching, the entire rotation surface could be fully unfolded, but the method could only be used for the detection of cylindrical bodies of revolution.

From the above-reviewed literature, the ODM-based expansion method adopts one-dimensional mechanical motion to replace the TDM in the traditional expansion method, avoiding the use of a complex deployment wheel system that is prone to wear and random deployment.

### 3.4. Detection environment

HRRS defect detection techniques carry out the inspecting process in two detection environments known as:

(a) **Air medium environment** [3–18, 21–65]: If there are no special requirements, HRRS defect detection is mostly performed by placing the measured workpiece in an air medium environment.

(b) **Other media environments** [19, 20]: If there are special requirements, HRRS defect detection can take place in other protective medium environments. Some media environments make it easier to find the defective area of a measured workpiece surface by weakening the reflection of the measured surface and thereby highlighting its defects. Wang et al. proposed an approach where a steel ball was placed in 10⁴ aviation hydraulic oil for detection of defects on the ball’s surface [19]. There were no light spots, halos or camera projections in the collected steel ball images.

### 4. Inspection techniques for HRRS defects

In this section, an overview of the existing defect detection methods for HRRS is presented. Defect detection systems (DDSs) for HRRS are applied to provide an indication of the quality of parts with highly reflective surfaces, remaining life prediction and remanufacturing. The traditional method of HRRS defect detection is a manual detection method; that is, an inspector visually observes the surface of a workpiece with a high-reflective surface under a fluorescent lamp and those that are abnormally reflective are considered defective. However, defect detection for HRRSs has traditionally been performed manually by skilled workers in a costly, tedious, strongly random and time-consuming operation. With advances in computers, robotics and sensor technologies, automated detection systems are quickly penetrating this area of operation, resulting in more accurate, efficient, safe and cost-effective solutions [46].

Automatic defect detection techniques for HRRSs have been investigated. In this review paper, the different existing automatic defect detection methods for HRRSs are classified into three groups: non-vision methods, vision methods and hybrid methods. While the first uses non-vision methods to perform non-destructive detection, different types of information such as the type, shape, location and size of surface defects are mainly obtained based on non-vision sensors such as fiber optic sensors, ultrasonic sensors, capacitance sensors, etc. The second uses machine vision, which extracts the shape features by pre-processing and enhancing the two-dimensional image of the workpiece surface to locate or segment the defects from the image to perform non-destructive detection. The last one combines various types of measurement techniques to achieve defect detection. This method fully integrates the advantages of various measurement techniques.

#### 4.1. Non-vision inspecting techniques for HRRS defects

In the past, researchers have investigated the field of non-vision detection methods for defects on HRRSs [10]. In the literature, based on their detection principle, non-vision defect detection approaches [11–16, 40, 47–58] are grouped as acoustic emission (AE) methods, photoelectric detection (PD) methods, EC methods, stylus methods, ultrasound methods, capacitive sensing (CS) methods, penetration methods, optical fiber sensing (OFS) methods, vibration value (VV) methods, etc. Specifically, the AE method is a passive non-destructive evaluation (NDE) technique that makes use of the high-frequency acoustic energy emitted by an object that is undergoing stress. According to the amplitude height and time domain width of the acoustic energy signal, the severity of defects can be identified. The PD method is a technique that uses the light that shines on the photo-resistor reflected by the surface of an object and judges whether there are defects on the surface of the object by the light intensity. The EC method is an important NDE technique that uses the electromagnetic induction principle to detect the surface defects of measured workpieces. In the stylus method, the profile of the workpiece surface is collected by a stylus to detect defects. In the ultrasound method, a transducer introduces ultrasonic waves into the measured workpiece, which travel in a straight line and at a constant speed until they encounter a surface. This causes some of the wave energy to be reflected, while the rest is transmitted. Analyzing the amount of reflected energy and transmitted energy provides information on the size and location of any defects encountered. The CS method is an NDE technique that uses the change of the detected capacitance to detect defects; for example, if the probe of the capacitance sensor and the surface of the measured steel ball are used as the two electrodes of the capacitance, when the surface of the steel ball appears defective, the capacitance capacity changes, and then the surface defects of the steel ball can be detected. In the penetration method, the penetrant infiltrates open defects on the surface of a non-metallic ball. After removing the penetrant on the surface of the ball, the shape, position and size of the defect can be shown by the penetrant which is infiltrated back from the defect. In the OFS method, a light beam emitted by a transmitting optical fiber is projected onto the surface of the measured workpiece. The defects on the surface of the workpiece affect the spot projected on the surface, and the reflected light on the surface changes. The defect size of...
Table 1. General evaluation of the non-visual methods for HRRS defect detection.

| Method          | Technique | Advantages                                      | Drawbacks                                                                 |
|-----------------|-----------|-------------------------------------------------|--------------------------------------------------------------------------|
| AE methods      | Acoustic emission | • Suitable for crack detection.                      | • Susceptible to environmental noise.                                      |
| PD methods      | Photoresistor | • Can detect finished balls.                       | • The optical path used is more complicated.                               |
| EC methods      | Eddy current   | • Ability to identify cracks.                      | • Does not identify minor scratches well.                                  |
| Stylus methods  | Stylus      | • Higher detection accuracy                       | • Easy to scratch the surface of the measured workpiece.                  |
| Ultrasound      | Ultrasound   | • Ability to detect planar defects and cracks more efficiently. | • Unable to identify small defects.                                       |
| CS methods      | Capacitance  | • Simple structure.                               | • Low detection accuracy.                                                 |
| Penetration     | Penetrant    | • Can detect the shape, location and size of defects | • Serious pollution on the ball surface.                                  |
| OFS methods     | Fiber optic  | • Small size.                                     | • Low detection efficiency.                                               |
| VV methods      | VV          | • Helpful for solving vibration and noise problems of the measured workpiece | • Damage to the measured workpiece during the detection process.          |

the workpiece surface can be detected by comparing the reference light intensity with the measured reflected light intensity of the measured workpiece surface. The VV method is a random sampling technology, which can detect the surface defects of the measured workpiece by measuring the VV of the workpiece.

The above-mentioned defect detection methods have their advantages and disadvantages. Each of the above methods was specifically introduced in the aforementioned review paper. To avoid any duplication, this paper will give an overall evaluation of the existing methods (as shown in table 1), which is not included in the aforementioned review paper. Table 1 provides a general evaluation of each method.

4.2. Vision inspecting techniques for HRRS defect

Benefiting from the fact that vision sensor technology can provide non-contact measurement, human preference for visual information, and the rapid development of computer image processing technology, many existing HRRS defect detection methods are based on the acquisition and processing of vision-based HRRS defect images. Vision-based HRRS defect detection methods are greatly affected by illumination. There are four illumination types:

4.2.1. Bright-field illumination. As shown in figure 3, the main idea of bright-field illumination technology is to position
Figure 3. Bright-field illumination: (a) curved surface with defects; (b) curved surface without defects.

Figure 4. Dark-field illumination: (a) curved surface without defects; (b) curved surface with defects.

a light source below the sample to perform surface detection of the workpiece. Due to the directionality of bright-field illumination, partial bright-field illumination can produce good contrast images [59]. If there is no defect on the inspected surface, the image is very bright. The presence of a defect will be a dark area on a bright background. Ng et al use vertical light from the top to the bottom for vertical bright-field illumination, where a ring light is placed between the workpiece and the CCD to illuminate the surface of the ball bearing under detection, thereby reducing specular reflection [17]. However, the area illuminated by the ring light is small and the ability to identify small defects is poor.

4.2.2. Dark-field illumination. The main idea of the dark-field illumination technique, as described in figure 4, is to set the angle of the light source and the relative position of the light source and the camera so that most of the light reflected from the measured surface will fall outside the field of view of the camera with the camera only ‘seeing’ scattered light that is reflected by a defect on the surface. If there are no defects in the measured surface, the captured image will be predominantly dark. If there are defects in the measured surface, the reflected light is no longer a parallel strong beam, but is scattered at the defects. Therefore, some of this scattered light will enter the camera and the presence of defects will figure as bright regions in the dark background of the captured image.

This illumination technique is suitable for the detection of high-reflection plane defects. The images captured using dark-field illumination have no specular reflection, good contrast and thus require fewer processing steps for segmentation of defects. However, when this illumination technique is used for defect detection of highly reflective curved surfaces with variable curvature, no matter how the angle of the light source is adjusted, there will still be a part of the highlighted area [46].

In order to reduce the intensity of the reflected light, Li et al tried to use a diffuse reflection flat plate light source to enter the surface of the steel ball. The reflected light from the steel ball surface entered the camera lens to detect the surface defects and the brightness of the diffuse reflection flat plate light source was adjustable [46]. However, the brightness of the flat panel light source is insufficient and the irradiation area is insufficient to act on the half surface of the ball. Yongtae et al put the measured object into a plastic cover with a transmittance of 70% [3]. Then, the entire surface of the steel ball could be inspected by capturing multiple grayscale images using two progressive CCD cameras. Zhao et al put the measured steel ball into a lightbox made of soft cloth to detect external defect areas of steel balls in bearings [18].

4.2.3. Uniform scattered light illumination. The main idea of uniform scattered light illumination technique, as described in figure 5, is to control the distribution of reflected light to make the reflected light evenly distributed. This has the advantage of greatly improving surface glare and reducing the data processing steps for certain applications [46].
Uniform scattered light illumination has been applied in the detection of highly reflective surfaces. In the beginning, Wang et al. used a diffuse spherical light source, which applied the light emitted by the LED to form scattered illumination light through the reflection of the arched bowl to achieve uniform illumination of the curved metal surface. Then, a ring-shaped diffuse reflection dome light source based on LED, which is an illumination light source with uniformly scattered light, was designed by Li et al. That is, a circular LED array and a dome-shaped diffuse reflection wall covering it were designed, and then the parallel light emitted by the LED was scattered multiple times on the diffuse reflection dome wall, and finally imaged on the CCD image plane. With this illumination method, the entire surface of the measured steel ball could not be completely inspected. Later, this illumination method was improved by Li et al. In this study, the authors made two observation holes on the dome-shaped diffuse reflection wall of the light source for capturing surface images of the measured entire steel ball, and a perforation on the wall to put the rail for supporting the steel ball in the vertical direction connecting the two observation holes. The results showed that the brightness of the improved illumination is sufficient and adjustable, the background is simple, and it is not affected by external light.

In recent years, several vision-based defect detection methods have been applied to solve high reflection interference problems in HRRS defect detection. The existing methods can be categorized into three of the following major groups according to the techniques they adopted: DEC-based methods, SL-based methods, and other methods. The related works of each group are listed in Table 2 and summarized in the following subsections.

4.2.4. DEC-based methods. The basic concept of DEC-based methods is to limit the detection environment in order to reduce the intensity of the reflected light and weaken the halo.

Figure 5. Irradiation principle of uniform scattered light illumination.

Metal balls play a dominant role in modern devices. To inspect surface defects on a metal ball surface that cause visual and electrical failure, Li et al. proposed an approach using a detection tank equipped with a service fluid and non-contact detection is performed on the steel ball to be tested. The service fluid needs to be transparent and regularly replaced, which can effectively shield external objects from imaging on the steel ball surface [20]. Zhao et al. proposed an approach using a lightbox made of soft cloth for the detection of defects on a metal ball surface; the steel ball image was collected in a specific closed soft cloth box to reduce the intensity of the reflected light and weaken the halo [18]. Wang and Lin proposed an approach using an oil medium to inspect defects in the highly reflective surface of a steel ball [19]. That is, for reducing the halo on the surface of a steel ball, the measured object can be put into an oil medium to realize the image collection of surface defects. Do and Lee proposed a vision-based method based on DEC, specifically, a 70% transparent plastic shade box was installed around the ball to lessen specular reflection of the metal surface [3].

4.2.5. SL-based methods. The basic concept of SL-based methods is to reduce the high reflection interference during the visual detection of high reflection surface defects by an SL system. There are two forms of obtained image in the HRRS defect visual detection based on the SL system: illumination non-mirroring-based and illumination mirroring-based images. Thus, in this review paper, the different existing SL-based visual detection methods for HRRS defect visual detection systems are classified into two groups: illumination non-mirror imaging (INMI) methods and illumination mirror imaging (IMI) methods.

4.2.5.1. INMI methods. The basic concept of INMI-based methods [21–29, 66–68] is to obtain images of the real measured workpieces, which can be represented in the form of grayscale images through visual detection under the SL system to complete the image acquisition of the measured workpieces.

For example, Valle et al. proposed a method using the light emitted from a light source hitting a properly designed non-planar mirror, which is reflected to illuminate the measured highly reflective curved surface, thereby achieving gray image collection and detection of the measured highly reflective surface defect. This method was experimentally verified by the detection of surface defects of a cylinder with a radius of 20 mm [21]. Li et al. and Ge et al. utilized cameras and microscopes with a combination illumination system, which consisted of coaxial and ring light sources, to implement visual detection of high-curvature surface defects of gyro pivot bearings [22, 23]. Song et al. designed a bowl-shaped red LED dome diffuse light source and used six CCD cameras to obtain the surface gray images of the steel balls [24]. Quan et al. designed an array pattern hole template, which can realize the batch feeding, rolling and detection of steel balls, and cooperates with SL equipment to solve the problems of the reflection of the polished surface of steel balls and the mutual projection between them [25]. Li et al. designed a circular diffuse dome light source based on LEDs [26]. To eliminate the shadows formed by surrounding objects and reflect bright spots, a circular LED array was designed that had a dome-shaped diffuse reflection wall above the circular LED array. Under this illumination, the images can be continuously collected by
the dual CCD camera during the rolling process of the ball row to realize the fully expanded collection of the ball surface. Zhang et al. used a stepper motor to control the rotation of the measured cylindrical workpiece, and a linear array camera to achieve the expanded gray image collection of the measured workpiece [27]. In order to ensure illumination uniformity of the measured workpiece, the two strip light sources are used for illumination and the incident angle between them is greater than 45°, which causes a certain overlap in the middle of the illumination area. Xu et al. developed a structured soft-light illumination system to overcome the difficulty of high-quality imaging of tiny and random defects on the cylindrical smooth surface of components such as pistons. Under this illumination system, the camera could be used to capture the surface gray images of the main piston of an automobile brake, so that the surface defects of the measured piston could be detected [28]. Chen proposed a method to achieve visual detection of defects on the cylindrical surface of a lens holder by using a CCD, a coaxial light and a motor unit [29].

4.2.5.2. IMI methods. The basic concept of IMI-based methods is to capture the mirror image of the light band modulated by the surface topography to finish the image collection of the measured workpieces. Ng et al. used a ring light to illuminate vertically from top to bottom, which produced a circular ring light band on the surface of a steel ball [17]. If there was a defect in the circular light band, the shape of the ring image of the light band changed. If the distance between the circular light source and the steel ball was continuously changed, the movement of the circular band could cover half the surface of the steel ball, and images of the steel ball could be collected. Le et al. proposed a method based on a CCD camera to capture the mirror images of the reflective band modulated by surface topography to realize the collection of surface defect images of a hemispherical workpiece [30]. Schmit et al. used a white light interferometer to convert the topographic features of the raceway or rolling element surface of a defective bearing to an interference fringe signal, and measured the three-dimensional topography of the measured surfaces by measuring the change of the interference fringes, thereby achieving precise measurement of surface defects [4]. Shao et al. designed an adaptive optical lighting system and used the striped illumination formed on the surface of the measured workpiece to realize the visual detection of high-reflection rotary surface defects. This method could effectively suppress the intensity over-exposure and halo interference caused by high reflection interference during the defect detection process [31].

4.2.6. Other methods. The basic concept of other methods (e.g. image processing-based methods) is to perform image processing on multiple images from different light sources to eliminate the image highlights and shadows caused by the strong reflection of the measured workpiece, and finally realize the visual detection of highly reflective surface defects. Zhang and Yoshioaka [32], under the optimized light source position, used a visual sensor to capture several images in different illumination directions and reconstructed the composite image to eliminate the bright areas caused by strong specular reflections. However, this method increases the complexity of subsequent image processing algorithms and is not suitable for rapid detection. Zhang and Ye [27] adopted the local binary pattern to reflect the spatial texture mode of local graphics and the local image variance intensity to highlight the image intensity contrast information, and then used the calculation result of the local image variance intensity as the weight value to adjust the extraction and measurement results of local texture. This method can effectively overcome the shortcomings of uneven illumination of metal materials and realize the automatic detection of surface defects on metal cylindrical workpieces.

4.2.7. Drawbacks of vision-based detection approach for HRRS defect detection. As mentioned in the previous sections, this vision-based detection approach is oriented towards one objective: solving high reflection interference problems. Some of these published papers [18, 19, 21–27, 32, 39, 43, 59–64] used the obtained two-dimensional visual image to give the light intensity change caused by the defect. However, surface stains will give a wrong signal, making it difficult to distinguish them from real defects, which increases the false detection rate. Further, because the HRRS is close to
the specular reflection, the brightness of the collected image is severely distorted, and a large halo is formed, so that the defect information that needs to be detected is not easy to reveal. Although some of these published papers placed the measured object in an oil medium [19], a plastic cover with 70% light transmittance [3], a lightbox (made of soft cloth) [18], etc., to reduce the intensity of reflected light and weakened halo, these methods reduced the brightness of the overall image and the highlights were still there. Thirdly, the specular reflection of the HRRS also caused the surface to easily map the surrounding scenes. Even if some of these published papers [3, 4, 18, 19] used the constraints of detecting the environment, there was a black area projected by the camera in the captured image. Therefore, the contrast conditions between the projection area and other parts is extremely large, which makes it difficult to distinguish the images. Fourthly, the contrast conditions are harsh and are greatly affected by light conditions, and its portability is not strong. If a non-planar mirror model is used, the light source is incident on the mirror surface and the light reflected by the mirror surface is incident on the highly reflective surface [21, 39], but the shape of the mirror needs to change according to the surface shape of the measured object. This model is not reproducible. If the surface shape of the measured object changes slightly, the relative positions of the camera, light source and mirror need to be recalculated and adjusted, and the portability is not strong. Finally, the collection speed problem: for example, Ng et al. use vertical light from the top to the bottom to generate a circular light band on the surface of a steel ball [17]. By continuously changing the distance between the ring light source and the steel ball, the surface ring images of the steel ball can be collected by a visual sensor. For images with feature regions, the image processing algorithm is used to determine whether there is a defect. This method in [17] well avoids the interference of specular reflections on HRRSs (highlight and shadow problems). However, the method in [17] is not suitable for rapid detection [17]. Similarly, Le et al. proposed a method based on a CCD camera to capture the mirror images of the reflective band modulated by surface morphology to achieve defect detection and determine the defect concavo-convex characteristics [30]. The method in [30] also avoids the interference of specular reflections, but the detection accuracy of this method is affected by the scanning interval and the speed is low, which is not suitable for rapid detection.

In general, the above-mentioned defect detection technologies for HRRSs cannot balance recognition accuracy, portability and efficiency, which restricts the application of these technologies.

4.3. Hybrid methods

In hybrid methods, it is common to use different sensing technologies (or sensors) to achieve defect detection. This is called multi-sensing-based detection technology. In order to fully integrate the advantages of various measurement sensors, in the past two decades, MSI measurement methods have emerged. The MSI method mainly uses two or more independent different sensors (contact probes, structured light sensors, vision sensors, etc) [34–36]. This method takes advantage of the combination and integration of the different sensors, reduces manual intervention and improves the speed, accuracy and integrity of digital measurement of freeform surfaces. For example, Chen et al. [34, 35] used optical vision sensors and contact probes to measure small holes with a diameter of 0.5 mm on the surface of rotary parts. Brandley et al. [36] integrated the line structured light sensor and the contact probe on a coordinate measuring machine. The line structured light sensor is used to perform a comprehensive scan of the measured surface, and a touch probe is used to manually measure the boundary features on the surface with higher accuracy requirements, etc. It can be seen from the above that the use of a composite sensor can achieve complementary measurement; that is, the measurement efficiency of the entire measured surface can be improved while ensuring the local measurement accuracy of the measured surface.

The AVIKO series of steel ball surface defect detection equipment (produced by Czech SOMET company) successfully applies a hybrid method, which integrates photoelectric and EC detection technologies to classify and count various defects and form an information system for defect screening [33]. However, AVIKO series products are expensive and difficult to maintain, which leads to higher testing costs. Zhu et al. presented a method for defect detection based on EC and laser sensors [65]. This method can effectively detect defects such as internal cracks, rust spots and scratches on a steel ball. The missed detection rate and false detection rate are below 0.04%, and the sorting speed can reach 30–90 particles per minute.

4.4. Comparison of HRRS defect inspecting techniques

To compare the performance of various methods, we have summarized the key attributes of a DDS for each technique in tables 3 and 4. These results are dependent on the confident research papers and reports which are referred to before. Table 3 shows the performance of existing defect inspecting techniques in terms of recognition accuracy, sensibility, transplantability, detection speed, etc. Table 4 shows the comparison of implementation characteristics based on several factors including cost, complexity and maintenance requirements. It can be seen from tables 3 and 4 that no method (or technique) is rated as ‘good’ on all key factors. The manual method has low detection efficiency, high cost and inaccurate results. Non-vision-based and vision-based automatic detection methods can be used to overcome these shortcomings, but the recognition accuracy, transplantability and efficiency cannot be compromised, which restricts the application of these technologies. However, the hybrid method can achieve complementary detection, that is, it can improve the detection efficiency of the entire measured surface while ensuring the local detection accuracy of the measured surface. However, various challenges are faced with this technology, especially in terms of cost, processing capabilities and maintenance. It is noted that the symbol (√) indicates function supported, the symbol (×) indicates function not supported and (—) indicates is not treated.
As shown in Table 3, the shortage of research works applying non-vision methods and hybrid methods compared to vision methods for HRRS defect detection is clear.

Figure 6 shows a quantitative summary of review articles for different methods used in HRRS DDSs. It can be seen that only a few papers were found describing non-visual measurement methods to achieve defect detection (e.g. there are a total of five papers on the EC methods and the number of papers on other non-visual methods is less than five). The reason is that application of non-visual methods is restricted due to detection accuracy, speed, etc.

Furthermore, as shown in Figure 6, only a few papers (a total of two papers) were found that describe hybrid measurement methods for defect detection. This is because researchers may face difficulties when trying to apply hybrid methods to the detection of HRRSs: different sensor technologies make it difficult to find accurate information fusion technologies between different sensors. For example, the accuracy of directly establishing the fusion model will affect the performance of the defect detection and recognition process, and constructing a high-fidelity mathematical model from such a complex system (e.g. HRRS detection system based on composite sensing) may become very complicated and time-consuming.

However, contrary to the lack of a hybrid-based method applied to high-reflective surface DDSs, this article found and reviewed more than 20 research papers that applied visual methods to the detection of high-reflective surface defects (as shown in Figure 6). The reason is that the visual method can provide non-contact measurement, the human preference for visual information and the rapid development of computer image processing technology, but the visual detection method is greatly affected by lighting, and an SL system needs to be designed to better achieve defect detection of HRRS workpieces.

### Table 3. Comparison of performance of defect inspecting techniques.

| Methods           | Accuracy | Sensibility | Easy transplanting | Speed | Quantitative (3D) |
|-------------------|----------|-------------|--------------------|-------|-------------------|
| Manual methods    | Low      | ×           | ✓                  | Low   | ×                 |
| Non-vision methods| AE [47, 48] | Low        | ×                  | ✓     | Low               |
|                   | PD [49, 50] | Medium     | ✓                  | ×     | Low               |
|                   | EC [40, 51–54] | Medium    | ×                  | ✓     | Medium            |
|                   | Stylus [55] | High       | ✓                  | ✓     | Low               |
|                   | Ultrasound [14] | Medium    | ×                  | ✓     | Medium            |
|                   | CS [15, 16] | Low        | ×                  | ✓     | Medium            |
|                   | Penetration [56] | Low     | ×                  | ✓     | Low               |
|                   | OFS [11–13] | Low        | ×                  | ✓     | Low               |
| Hybrid methods [33, 65] | High     | ✓           | ✓                  | Medium | ✓ (or ×) |

### Table 4. Comparison of implementation characteristics of defect inspecting techniques.

| Methods           | Cost | Complex operation | Maintenance |
|-------------------|------|-------------------|-------------|
| Manual methods    | High | ×                 | Low         |
| Non-vision methods| AE   | Low               | Medium      |
|                   | PD   | Medium            | Medium      |
|                   | EC   | Medium            | Medium      |
|                   | Stylus | Low               | Medium      |
|                   | Ultrasound | Low       | Medium      |
|                   | CS   | Low               | Medium      |
|                   | Penetration | Low       | Medium      |
|                   | OFS  | Low               | Medium      |
| Vision methods    | DEC  | Low               | Medium      |
|                   | SL   | Low               | Medium      |
|                   | Other | Low               | Low         |
| Hybrid methods    | High | ✓                 | High        |

4.5 Evaluation of defect detection

There is little literature on the evaluation of HRRS defect detection. In the evaluation process of HRRS defect detection, it is mainly to evaluate the detection results of machine vision method, that is to comprehensively compare various indicators (the recall rate, accuracy, missing rate, false detection rate, false classification, detection speed, etc) of the same surface image.

In addition to the above methods, detection uncertainty can also be used to evaluate the defect detection results. Detection uncertainty is a measure of possible error of test results and is a parameter closely related to detection results. With the improvement of detection accuracy, the evaluation of uncertainty of test results becomes increasingly important. Detection uncertainty can arise from several sources such as detection setup, environment, operator influences, finite sampling, etc. However, there is little literature on uncertainty.
evaluation in defect detection. For example, the approach described in Ren et al [69] for analyzing measurement uncertainty of defect depth in ultrasonic-based defect detection enables uncertainties to be calculated in accordance with the GUM [70]. In [69], the main sources of uncertainty in ultrasonic detecting are the horizontal linear error of the ultrasonic defect detection device, the performance of the angle probe and the specification of the test block. Therefore, in order to obtain accurate detection results, the horizontal linear error of the ultrasonic defect detection device should be checked before testing to ensure that it is in the appropriate range, and then selecting the appropriate probe and test block.

5. Conclusion and outlook

Precise rotating parts with HRRS are widely used in aviation, aerospace, railways, precision machine tools, automobiles and other fields. However, such parts may produce surface defects during their production and post-processing. Unfortunately, surface defects can affect the performance and lifespan of a product, and even cause serious accidents and major economic losses. For this purpose, inspecting the surface quality of such parts has become a major challenge. The main interest of this article is to provide a comprehensive overview and summary of the existing defect detection methods for the characteristics of high-reflection surface defect detection. Therefore, this article first introduces the special challenges that must be faced in the detection of highly reflective surface defects. Then, the different detection methods of different high reflection surface DDSs are classified. These different detection methods are classified into non-visual methods, visual methods and hybrid methods according to whether they use visual sensing or not. Among them, the visual methods can be classified into DEC methods, SL methods and other methods. In addition, this article also compares and analyzes various defect detection methods based on different key features, which helps to determine the feasibility of different methods.

According to the detecting requirements and challenges of HRRSs, such as high precision and cost saving, multi-sensor techniques can be used to ensure detection speed and improve detection accuracy. Non-destructive detection techniques have their advantages and limitations in the process of identifying defects on HRRSs; that is, it is difficult for a single detection method to achieve fast, accurate and comprehensive detection. In practical applications, the fusion of two or more detection techniques to merge the advantages of different sensing techniques can further improve the defect detection recognition rate and other indicators, which may become a major trend in the future.

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ORCID iD

Awei Zhou  https://orcid.org/0000-0002-3957-1068

References

[1] Apking A 2018 MultiClient Study: Worldwide Market for Railway Industries 2018 (Köln: SCI Verkehr GmbH)
[2] Apking A 2019 MultiClient Study: Light Rail Vehicles—Global Market Trends 2019 (Köln: SCI Verkehr GmbH)
[3] Do Y, Lee S and Kim Y 2011 Vision-based surface defect inspection of metal balls Meas. Sci. Technol. 22 107001
[4] Schmit J, Han S and Novak E 2009 Ball bearing measurement with white light interferometry Proc. SPIE the Int. Society for Optical Engineering (Munich, Germany, June) pp 15–16
[5] Wang P 2008 Detection of steel ball surface defect based on motion vision PhD Thesis Harbin University of Science and Technology
[6] Zhao Y 2008 Analysis and identification for surface defects of steel ball based on image technology PhD Thesis Harbin University of Science and Technology

[7] Liu Q, Zhang J and Huang J 2013 Detection and classification for surface defects of steel balls based on machine vision Meas. Sci. Technol. 24 44–53

[8] Lin Y, Liu X, Han H, Wang Y and Wang P 2009 Detection and recognition of steel ball surface defect based on MATLAB Key Eng. Mater. 416 603–8

[9] Pan W and Zhao X 2014 Measurement of steel ball surface flaw based on dual wavelength interferometry and digital phase detection Chin. J. Lasers 41 (05)08007

[10] Zhou H, Dong C, Chen F, Cheng L, Wu C and Weng H 2018 A review on detection method of steel ball surface defect Equip. Manuf. Technol. 10 7–11,47

[11] Wang C L, Ai C S and Li G P 2014 Optical fiber sensor system for detecting the steel ball surface quality Appl. Mech. Mater. 654 245–53

[12] Zhang Y 2011 Defects inspection of steel ball based on optical fiber sensing technique ME Thesis University of Jinan

[13] Wang C 2014 Research on multi-fiber detection method of steel ball surface defects ME Thesis University of Jinan

[14] Xu S and Jiang Y 2005 Ultrasonic testing for bearing balls with defects Mach. Build. Autom. 34 44–5,49

[15] Kakimoto A 1996 Detection of surface defects on steel balls in production process using a capacitive sensor Measurement 17 51–7

[16] Ma Y and Li G 2012 Detection on surface defect of large length scale steel balls Transducer Microsyst. Technol. 31 144–6

[17] Ng T W 2007 Optical inspection of ball bearing defects Meas. Sci. Technol. 18 N73–N76

[18] Zhao Y, Wang P, Hao H and Liu X 2008 The embedded control system of vision inspecting instrument for steel ball surface defect Proc. 20th IEEE Chinese Control and Decision Conf. (Yantai, China, July) pp 7–9

[19] Wang Y, Lin Y, Jia D, Zhang Z and Liu X 2010 Comparative analysis on inspection of steel ball surface defect in air and oil medium Bearing 5 37–9,42

[20] Li C 2005 Steel ball appearance measurement system based on image processing Bearing 9 36–8

[21] Valle M, Gallina P and Gasparetto A 2003 Mirror synthesis in a mechatronic system for superficial defect detection IEEE/ASME Trans. Mech. 8 309–17

[22] Li X, Ge W and Zhao H 2009 Research of defects detection on metal axis tip surface and dimension measurement system Comput. Eng. Des. 30 1777–9

[23] Ge W, Zhao H and Li X 2011 Gyroscope pivot bearing dimension and surface defect detection Sensors 11 3227–48

[24] Song X, Yang J and Xu H 2010 Method for surface defect detection of steel ball based on machine vision Bearing 5 45–8

[25] Quan Y, Chen J and He Z 2010 Image preprocessing method for automatically batch detection of steel balls surface defects J. Test Meas. Technol. 24 518–21

[26] Li L, Wang Z and Pei F 2013 Improved illumination for vision-based defect inspection of highly reflective metal surface Chin. Opt. Lett. 11 021102

[27] Zhang J, Ye Y, Xie Y, Liu L and Chang Y 2014 Optoelectronic inspection of defects for metal cylindrical workpieces Opt. Precis. Eng. 22 1871–6

[28] Xu L M, Yang Z Q, Jiang Z H and Chen Y 2017 Light source optimization for automatic visual inspection of piston surface defects Int. J. Adv. Manuf. Technol. 91 2245–56

[29] Chen S H 2017 Fast defect inspection of high-resolution and textured cylindrical lens holder surface using randomized SVD Nondestruct. Test. Eval. 32 59–78

[30] Le J, Guo J, Zhu H, Fang H and Shao W 2004 A fast defect-detecting method for smooth hemispherical shell surface Opto-Electron. Eng. 31 32–5

[31] Shao W, Liu K, Shao Y and Zhou A 2019 Smooth surface visual imaging method for eliminating high reflection disturbance Sensors 19 4953

[32] Zhang Z, Yoshikura H, Imamura T and Miyake T 2013 Optimization of light-source position in appearance inspection for surface with specular reflection Proc. IEEE Int. Conf. on Information and Automation August Yinchuan, China

[33] Kurosawa Y 1998 Subspace method obtained from Gaussian distribution on a hyper spherical surface Trans. Inst. Electron. Inf. Commun. Eng. 81 32–9

[34] Chen X, Longstaff A, Fletcher S and Myers A 2014 Deployment and evaluation of a dual-sensor autofocus method for on-machine measurement of patterns of small holes on freeform surfaces Appl. Opt. 53 2246–55

[35] Chen X, Longstaff A, Fletcher S and Myers A 2014 Analysing and evaluating a dual-sensor autofocus method for measuring the position of patterns of small holes on complex curved surfaces Sensors Actuators A 210 86–94

[36] Bradley C and Chavan V H 2001 A complementary sensor approach to reverse engineering J. Manuf. Sci. Eng. 123 74–82

[37] Zhou A, Guo J, Shao W and Li B 2013 A segmental calibration method for a miniature serial-link coordinate measuring machine using a compound calibration artefact Meas. Sci. Technol. 24 065001

[38] Zhou A, Guo J, Shao W and Yang J 2013 Multipurpose measurement of surface defects on rotary metal parts with a combined laser-and-camera sensor Opt. Eng. 52 104104

[39] Rosati G, Boschetti G, Biondi A and Rossi A 2009 Real-time defect detection on highly reflective curved surfaces Opt. Lasers Eng. 47 379–84

[40] Zhang Y 2007 Analysis of eddy current detector used for testing surface flaw of steel ball J. Harbin Bearing 28 32–3

[41] Pan H 2000 A study on the building and applications of automatic appraise system for surface quality of steel balls PhD Thesis Harbin Institute of Technology

[42] Wang H and Xu C 2009 The development of surface warp and woof unfolded system in the steel ball detection Comput. Knowl. Technol. 5 3505–7

[43] Wang Y, Ding K, Jia D, Liu X, Yue C and Zhao Z 2010 Kinematic analysis of detection of steel ball surface defect based on ADAMS Adv. Mater. Res. 102–104 83–7

[44] Zhao Y, Liu Y and Hao H 2009 Unfolding device of steel ball surface defects China Patent, CN 201373822Y

[45] Wang Z, Pei F and Li L 2011 Method and device for unfolding steel ball surface based on multi-image sensor China Patent, CN 201110227679.4

[46] Li L 2013 Study on the key technology of surface defects inspection on highly reflective sphere based on vision PhD Thesis Tianjin University

[47] Xu S and Jiang Y 2003 Acoustic emission testing of bearing balls Nondestruct. Test. 25 358–9

[48] Hamel M, Addali A and Mba D 2014 Investigation of the influence of oil film thickness on helical gear defect detection using acoustic emission Appl. Acoust. 79 42–6

[49] Zhang K 2000 Analysis of Japan NSK new type rolling bearing Bearing 9 36–8

[50] Zhao G and Ma S 1997 Theoretical analysis of the meridian expansion mechanism of the Aviko K steel ball appearance inspection machine J. Sichuan Univ. 34 635–9

[51] Zhang H, Xie F, Cao M and Zhong M 2017 A steel ball surface quality inspection method based on a
circumferential eddy current array sensor Sensors 17 1536
[52] Ai C, Yu R, Sun X, Zhang H and Shen W 2009 Research on quality inspection and sorting on-line system for bearing steel ball Meas. Control Technol. 28 4–7
[53] Xu C, Gao C and Weng K 2007 Study of steel ball surface detection system Meas. Control Technol. 26 85–7
[54] Wang S and Lei Y 2014 Recognition method for surface defects on steel ball Nondestruct. Test. 3 1–4
[55] Wang Z, Gao Y, Huang Y, Hu S and Gao Z 1998 Detection of surface roughness by using micro-imaging Opt. Technol. 5 47–9,46
[56] Li Z, Wu N, Gu B and Wang Z 2003 Penetrant inspection and automatic sorting system for ceramic bearing balls Nondestruct. Test. 25 296–301
[57] Pan H, Dong S and Liang Y 2001 A new method of detection for steel ball’s vibration value based on image texture feature Chin. Mech. Eng. 12 174–6
[58] Jiang H 2002 Effect of steel geometric accuracy and surface quality of steel ball on the single ball vibration Mech. Eng. 5 45
[59] Boby R A, Sonakar P S, Singaperumal M and Ramamoorthy B 2011 Identification of defects on highly reflective ring components and analysis using machine vision Int. J. Adv. Manuf. Technol. 52 217–33
[60] Aluze D, Merienne F, Dumont C and Gorria P 2002 Vision system for defect imaging, detection, and characterization on a specular surface of a 3D object Image Vis. Comput. 20 569–80
[61] Sills K, Bone G M and Capson D 2014 Defect identification on specular machined surfaces Mach. Vis. Appl. 25 377–88
[62] Pan H, Dong S, Liang Y and Xie S 2001 Automatic detection and recognition of steel ball’s surface flaws Chin. Mech. Eng. 12 569–71
[63] Wang P, Zhao Y, Liu X and Wang Y 2008 The key technology research for vision inspecting instrument of steel ball surface defect Key Eng. Mater. 392 816–20
[64] Zhao H, Ge W and Li X 2012 Modified-PCNN based detection of gyroscope pivot surface defects J. Beijig Univ. Aeronaut. Astronaut. 38 340–4
[65] Zhu L, Zha L, Leng Z and Zhang Q 2010 Research of the steelball flaw detection system Mach. Des. Manuf. 7 122–4
[66] Chen Y J, Tsai J C and Hsu Y C 2016 A real-time surface inspection system for precision steel balls based on machine vision Meas. Sci. Technol. 27 074010
[67] Wang Z, Xing Q, Fu L and Sun H 2015 Realtime vision-based surface defect inspection of steel balls Trans. Tianjin Univ. 21 76–82
[68] Shen H, Li S, Gu D and Chang H 2012 Bearing defect inspection based on machine vision Measurement 45 719–33
[69] Ren G, Cui D, Hu Z and Wang Y 2014 Uncertainty evaluation on weld defect depth inspected by ultrasonic Phys. Test A 50 744–7
[70] ISO(International Organisation for Standardization)/IEC(International Electrotechnical Commission) 2011 Uncertainty of Measurement—Part 3: Guide to the Expression of Uncertainty in Measurement (Gum:1995)—Supplement 2: Extension to Any Number of Output Quantities 1st edn (Geneva: Joint Committee for Guides in Metrology)