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A critical review for machining positioning based on computer vision

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ABSTRACT

With the rapid development of science and technology, the manufacturing industry has to cope with increasingly stricter requirements in terms of the quality of processed products. To improve production flexibility and automation, computer vision is widely used in machining due to its safety, reliability, continuity, high accuracy, and real-time performance. In this study, a comprehensive review of positioning methods for workpieces in machining is presented from the perspective of computer vision technology. First, the key technologies in image acquisition are described in detail, and a analysis of different lighting modes is conducted. Second, image preprocessing is described by summarizing enhancement and image segmentation methods. Third, from the perspectives of accuracy and speed, feature extraction methods are compared and evaluated. Next, the existing applications of visual positioning technology in machining are discussed. Finally, the existing problems are summarized, and future research directions technology suggested.

1. Introduction

In recent years, with the rapid development of artificial intelligence, research on computer vision has progressed significantly. Visual positioning technology, based on computer vision, is currently one of the key research topics. Unlike traditional positioning technology, visual positioning technology utilizes visual information effectively to achieve dynamic target tracking, model reconstruction, and real-time processing. Therefore, research on positioning processing methods based on computer vision is important to identify application prospects for such methods.

In the manufacturing industry, processing methods such as traditional machine tool processing [1], electric discharge processing [2], laser processing [3,4], ultrasonic processing [5], and high-pressure water jet processing [6] are being upgraded to obtain high-precision products. Flexible automation of workpieces has been realized using computer numerical control (CNC) machine tools. However, flexible automation has not been achieved in terms of precise positioning of workpieces. Two techniques are mainly used for high-precision installation and positioning of workpieces. In the first technique, workpieces are placed on the machine tool manually and then measured manually to the correct processing position [7]. The other technique is to design a special high-precision fixture according to the characteristics of the machining parts and processes and then installing the fixture accurately on the machine tool. The relative positioning of workpieces is performed through close contact of the datum planes between the workpieces and the fixture. As the accuracy requirements in product processing become increasingly stringent, traditional positioning methods cannot satisfy the demand for high precision, efficiency, automation, and flexibility, due to fixture wear, environmental impact, and human factors. Visual positioning technology provides an innovative solution for traditional positioning processing [8]. The visual positioning system for machining (Fig. 1) is mainly composed of an image acquisition subsystem, an information conversion subsystem (computer system), positioning algorithms, and a processing subsystem. The visual positioning system uses suitable light sources and image sensors (CCD camera) to obtain workpiece images. Corresponding image positioning algorithms (image preprocessing, edge detection, feature extraction, etc.) are adopted to extract the edge and position information of the images, and the workpieces are finally processed (cutting, drilling, welding, etc.) through executive part. With continuous improvements in industrial automation, the application of visual positioning systems in the industry is becoming increasingly widespread.

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Nomenclature

CNC	Computer numerical control
CNN	Convolutional neural network
DOF	Depth of field
EDM	Electric discharge machining
FCN	Fully convolutional networks
GA	Genetic algorithm
GAN	Generative Adversarial Network
GoogleNet	Google inception Net
PCB	Printed circuit board
PMD	Phase measurement deflection
PSO	Particle swarm optimization
RBF	Radial basis function
R-CNN	Region-CNN
ReNet	Recurrent Neural Network
ResNet	Residential Networking
SIFT	Scale-invariant feature transform
SSD	Single shot multibox detector
SURF	Speeded up robust features
VGG	Visual geometry group

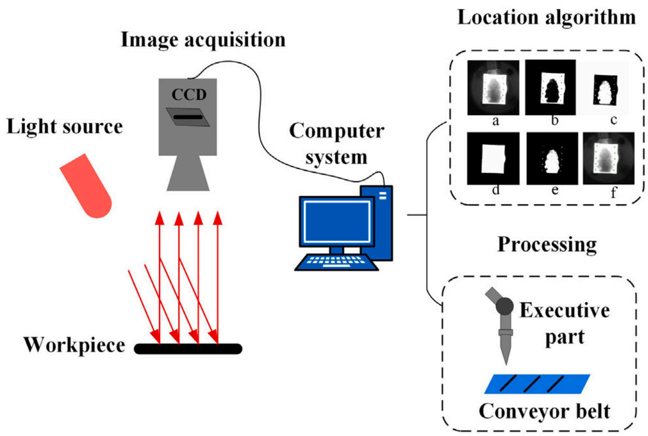


Fig. 1. The work flow of vision system in workpieces positioning processing.

The combination of visual positioning technology and robotic arms will be a major breakthrough in the industrial manufacturing. The appearance of drilling robot arm with positioning function [9], mechanical system for automatically positioning and accurate placement of workpiece [10], and various automatic positioning solutions based on vision [11] have brought unprecedented high precision to the manufacturing industry, and set off a research boom of visual positioning processing methods. Scholars have carried out a lot of the technical exploration and practice. Ouyang (2016) et al. [12] proposed that visual positioning can be applied to plate processing positioning (automatic feeding positioning by punch press, automatic feeding positioning by laser processing line), which has higher positioning accuracy than mechanical positioning and sensor positioning. Grinding positioning processing system based on machine vision also has been proved to have good positioning capabilities [13], which can perform workpiece positioning and grasping and accurate grinding of workpiece surface burrs under complex background conditions. Wan (2019) et al. [14] proposed a shape-based template matching method combining linear algorithm and Region of Interest (ROI) area to locate rough-machined castings, which can find rough objects at a high calculation speed with good robustness. According to the experiments, the repeatability of the system is within 2 mm, verifying the feasibility of the method and the robustness of the algorithm. Chen (2019) et al. [15] improved feature matching with the combination of the traditional oriented fast and rotated brief algorithm and the random sampling consensus algorithm. Based on the consistency of distance, rotation and Angle of the correctly matched point pairs, the improved algorithm obtains the mismatched point pairs in advance to improve the poor real-time performance and low precision of the image matching technology. Hou (2020) et al. [16] proposed a welding robot positioning method based on machine vision and laser ranging to solve the problem of precise positioning of welding robots in automated bar production, with certain reference significance for the motion control of welding robots. Liu (2020) et al. [17] developed an intelligent vision CNC cutting system that integrates control and vision technology. This system can identify feature points to perform cutting, and the correct recognition rate of marked points is as high as 98%. The system has been applied in batch production. Ni (2020) et al. [18] designed a vision-based microelectronic device positioning scheme, which combines the boundary tracking algorithm and template matching algorithm of binary images to accurately position electronic products on the assembly line, showing that the positioning accuracy of the proposed method is 0.2 mm with certain practical value for the positioning and processing of electronic products.

Positioning is a vital step in workpieces processing, the accuracy of which affects the precision of workpieces directly. Computer vision-assisted positioning of workpieces is expected to become the mainstream trend in machining. In this study, methods of workpiece positioning in machining are reviewed from the perspective of the computer vision technology (image acquisition, image preprocessing, feature extraction, etc.). Therefore, a structure diagram of workpiece positioning based on computer vision in machining (traditional and non-traditional machining) is provided in Fig. 2. In Section 2, the key technologies used in machine vision systems are discussed in detail, and the hardware performance (light source, lens, etc.) in different systems is compared. Image preprocessing is the prerequisite for processing and positioning the workpiece, and good image preprocessing can make the positioning of the workpiece more accurate. Therefore, Section 3 reviews image preprocessing methods(image segmentation and image enhancement) used for workpiece positioning in machining and compares their advantages and disadvantages. In Section 4, the methods used for feature extraction of workpieces in machining positioning are listed. In addition, these methods are divided into three categories traditional, template matching and deep learning algorithms and their advantages and disadvantages are compared. Section 5 reviews the applications of traditional, non-traditional machining and printed circuit board (PCB) machining for workpiece positioning. Finally, the future development of visual positioning technology is discussed.

2. Optical systems

As depicted in Fig. 3, the computer vision system for machining positioning includes hardware (light source, lens, camera, etc.), software, and execution components. In a visual positioning system, the most critical technologies are light source, optical lens, image acquisition, and image processing. The selection of the lighting source, optical lens in the optical imaging system, and the camera required for image acquisition are the key to the success of the vision system.

2.1. Light source

In a visual positioning system, an external light source is commonly used to illuminate the workpieces. The light source is required to provide the best lighting condition for each position of the workpiece without being affected by the external ambient light. The images obtained via image acquisition should highlight the features of the workpieces as much as possible and should have sufficient overall brightness [19]. Common light sources include incandescent lamps [20],

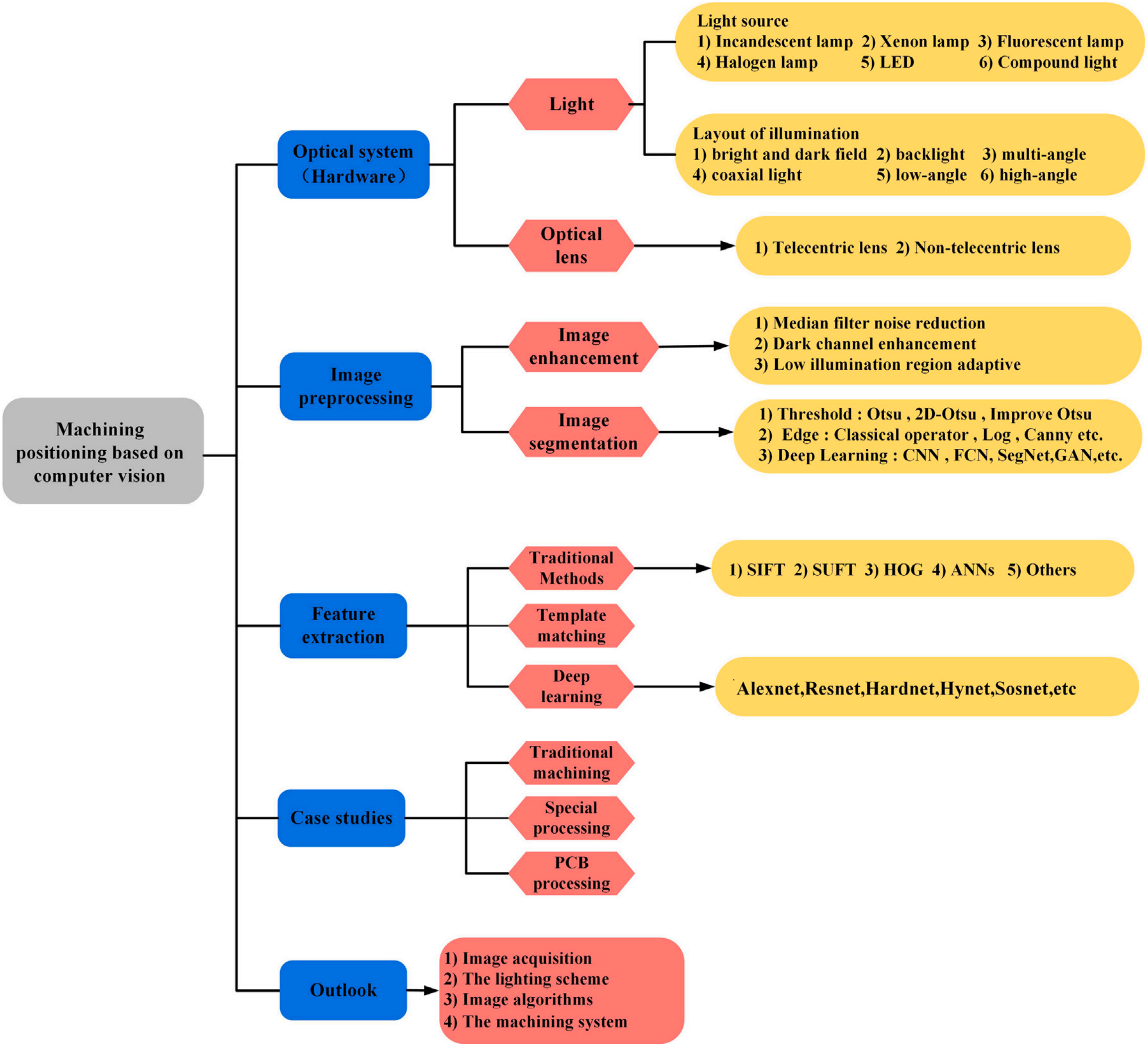


Fig. 2. The structure diagram of comprehensive review: machining positioning based on computer vision.

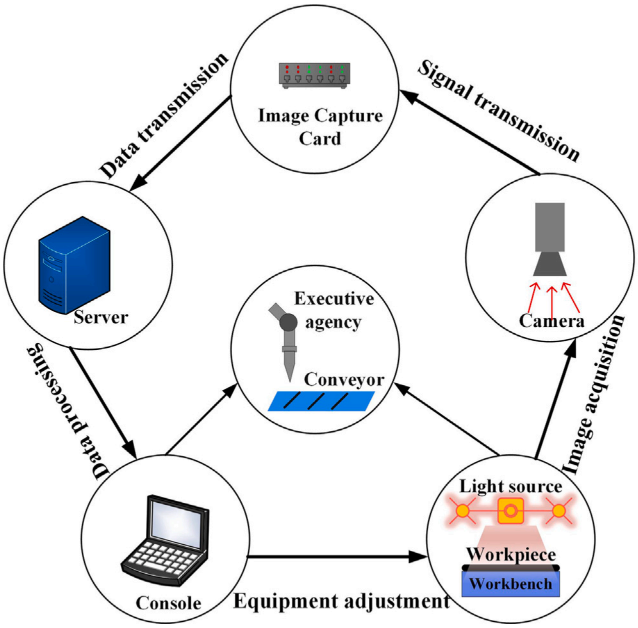


Fig. 3. The overview of computer vision system for machining positioning.

xenon lamps [21], fluorescent lamps [22], halogen lamps [23], and LED [24]. Among these, incandescent lamps have essentially become obsolete. With the continuous development of lighting technology, scholars have focused on composite light sources (combined light) [25, 26]. A performance comparison between different light sources is provided in Table 1.

Through comparisons between several key parameters, such as service life, light efficiency, brightness, power consumption, and heat generation, of several light sources, it was found that the overall performance of LED lights is significantly better than that of other light sources [27]. For a visual positioning system, a stable, uniform, and suitable light source is indispensable [27,28]. Compared with traditional light sources, LED lights offer a stable luminous intensity, long life, and convenient adjustment. In the selection of a light source, factors such as economic cost and processing environment must also be comprehensively considered. In view of all the aforementioned factors, LED lights represent the most suitable choice of lighting source for a computer vision positioning system.

According to the brightness/darkness of the view field, the relative position of the workpieces, and the angle of illumination, light sources can be divided into bright- and dark-field illumination, back lighting, forward small-angle and forward high-angle illumination, multi-angle illumination, and coaxial illumination. Fig. 4 depicts the layout of illumination for machining positioning. As shown in Fig. 4(a), the reflected light entering the camera from inside the “W” region can be classified as the bright-field illumination; the obtained image contrast is exceedingly high. On the contrary, when passing outside the “W” region, the lens receives diffuse light, and the light on the smooth surface is reflected out. Therefore, the surface image of the uneven workpiece can be obtained [29]. Fig. 4(b) displays back light illumination for workpiece positioning. The contour of the image obtained using the lighting layout is clear and is suitable for detecting the size and shape of the workpieces [30]. Fig. 4(c) shows multi-angle lighting, where light illuminates the surface of the workpieces from different angles. The overall illumination of the target is relatively uniform, but the illumination area is relatively small. Therefore, this lighting layout is suitable mainly for the detection of curved workpieces [31]. Fig. 4(d) shows coaxial illumination, in which light tends to be parallel and more resistant to external interference [32]. This layout is mainly used for semiconductors, PCB boards, and positioning processing of metal parts [33]. Fig. 4(e) depicts low-angle illumination, which has a strong ability to express the unevenness of a surface and is therefore suitable for detection of workpieces with uneven surfaces [34]. Fig. 4(f) shows high-angle illumination, which offers advantages such as a concentrated beam, high brightness, and good uniformity. This method is often used for the positioning of small parts (such as bolts) [35].

2.2. Optical lens

The optical lens is an indispensable component in a vision system, and its main function is optical imaging. Therefore, the quality of the lens directly affects the effeteness of the image. According to literature, lenses can be divided into telecentric (Fig. 5(a)) and non-telecentric (Fig. 5(b)) types. The former is unique because it has zero parallax. The lens parameters mainly include focal length, resolution, field of view, and depth of field. [37,38], as shown in Fig. 5(c). Within a certain range of object distance, the magnification of an image captured by a telecentric lens will not change with variations in the object distance.

With the rapid development of computer vision, scholars are increasingly studying the applications of lenses. Ordinary lenses can no longer satisfy the requirements of vision systems due to parallax. Therefore, such lenses are gradually being replaced by telecentric lenses. A telecentric lens is a special lens designed to correct the parallax of the traditional industrial lenses [39]. According to application requirements, Chen et al. [40] adopted a telecentric lens placed coaxially with a ring light source to provide stable illumination for a vision system. Jing et al. [41] designed a large-magnification object-side telecentric lens with a C-mount. The lens has 4 × magnification, a 65 mm object-side working distance, a 0.1 degree telecentric angle, and 0.3% distortion and can be used for the positioning and monitoring of touch screen defects online. For precise measurement of large parts, Zhang et al. [42] designed a set of aspheric double telecentric lenses. Experiments demonstrated that the lens had a depth of field of 80 mm, a maximum distortion of 0.05%, and a telecentricity of less than 0.01 degree, which satisfy modern positioning requirements. For complex workpieces and shaft parts, scholars have designed suitable telecentric lens. To prevent the chromatic aberration in the imaging process, Yang et al. [43] designed a high-resolution, wide-field apochromatic lenses to overcome the optical path difference between different-colored lights. They found that after using the Buchdahl dispersion vector method to replace a part of the glass material optimization, the lens could meet the design requirements, i.e., no chromatic aberration and 30% resolution in the objective space. For the measurement of three-dimensional mirror objects, Niu et al. [44] proposed an advanced phase measurement deflection (PMD) method based on a novel mathematical model, which uses a double telecentric lens to obtain the three-dimensional shape of discontinuous mirror objects. Sun et al. [45] discussed the methods of calibrating vision systems with telecentric lenses and conducted positioning experiments on metal workpieces with holes. Experimental results revealed that the maximum relative error of the main dimensions of the workpieces was less than 0.51%, which is sufficient to satisfy the positioning requirements. Li et al. [46] proposed a contour error detection method for CNC machine tools based on monocular vision. Because of their constant enlargement ratio, low imaging distortion, and large depth of field (DOF), telecentric lenses were used as the optical systems. Compared with that of systems having traditional lenses, the accuracy of imaging systems having telecentric lenses and a calibration camera was higher, and the average measurement accuracy was 4.2 μm. Table 2 summarizes the lenses in the above literatures.

In summary, telecentric lenses are mainly designed to correct the parallax of traditional lenses and to avoid “near large far small” situations. Compared with traditional lenses, telecentric lenses have a higher depth of field, lower distortion, no parallax, and higher magnification. Particularly, telecentric lenses will not introduce any uncertainty to the image edge position, because of the geometric characteristics of the visual light source. Thus, such lenses are suitable for the positioning processing, size measurement, and classification recognition of parts with various sizes. Considering the convenience and functionality of practical applications (such as depth of field, parallax, distortion, positioning accuracy, and other factors), double telecentric lenses combined with appropriate light sources are usually used in visual positioning systems for image acquisition.

2.3. The camera characteristics and calibration

Camera calibration is divided into internal parameter calibration and external parameter calibration, with the purpose to determine the corresponding relationship between the target object in the image coordinate system and the world coordinate system [47], which needs to establish an imaging geometric model, with the premise of obtaining camera parameters as the process. Therefore, after the visual positioning system is installed, it is necessary to establish a multi-coordinate system relationship and eliminate camera distortion through camera calibration to establish an image geometric model and eliminate distortion.

The camera obtains the geometric information of the object to be processed by shooting images. In order to improve the efficiency and accuracy of positioning in machining, many scholars have dedicated to the research of camera calibration methods with the results as the basis for subsequent positioning, which has been proved to improve the positioning accuracy [48]. However, there are also some problems such as cumbersome calibration process, large amount of calculation, long calibration process time, and unstable results. With the rapid development of machine vision, the theory and technology of camera calibration have also been developed. Ding et al. [49] combined the calibration method with the artificial neural network, which verified that this algorithm has higher calibration accuracy and generalization ability than traditional calibration algorithms, with faster convergence rate than traditional artificial neural network structures. However, they idealized the model without considering the relationship between the parameters. Wang et al. [50] proposed an improved calibration algorithm to improve the accuracy of chip positioning according to the error analysis results of the vision system and the characteristics of the chip positioning process, which has been verified that the system error of the positioning system is about 6 μm after using the improved calibration algorithm. However, the visual positioning system is mainly used for the two-dimensional positioning of the chip, while the algorithm focuses on the study of the external parameters of the camera, ignoring the influence of the internal parameters of the camera on the entire system. Chen et al. [51] put forward an improved nine-dot-based camera self-calibration method to solve the problems of poor anti-noise performance and low accuracy in the current monocular camera calibration algorithms for laser cutting vision systems, which is applicable in laser cutting, with unclear calibration effect in other machining. Some calibration algorithms in recent years are listed in Table 3. By analyzing and summarizing these calibration algorithms,

Table 1
Performance comparison of common light sources in machining positioning system.

Type of light source	Color	Life/h; Brightness;Power/w	Advantage	Disadvantage
Incandescent lamp [20]	White with light yellow	1000–3000h;Very bright;25–100 w	Low cost, good color rendering	Low luminous efficiency, short life
Xenon lamp [21]	White with light blue	3000–6000 h;Brighter;50–150 w	High Brightness	Short life
Fluorescent lamp [22]	White with light green	5000–7000 h;Brighter;50–100 w	Long life and low heat dissipation	Chromatic aberration
Halogen lamp [23]	White with light yellow	5000–7000 h;Brighter;20–100 w	High luminous efficiency	Generate more heat
LED [24]	Warm White, Fair White, and Cold White	50000–100000 h;Bright;1–7 w	Good color rendering performance, concentrated beam	High thermal dependence, poor heat dissipation
Compound light [36]	Multiple color	Stability, adjustable light source brightness and intensity	The controllability of color and brightness	Combination of multiple LED lights

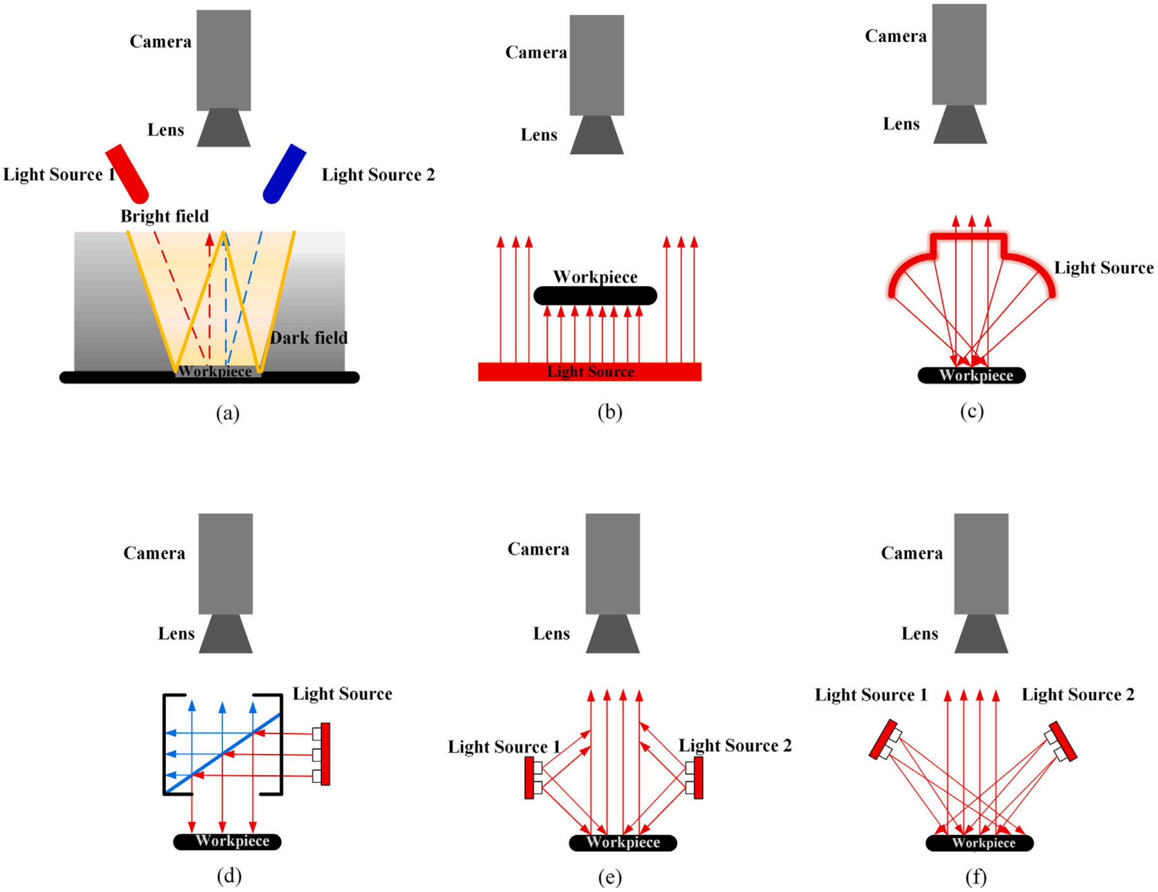


Fig. 4. Layout of illumination for machining positioning (a) bright and dark field illumination [29]; (b) backlight illumination [30]; (c) multi-angle illumination [31]; (d) coaxial light illumination [32]; (e) low-angle illumination [34]; (f) high-angle illumination [35].

the general development direction of the calibration methods in the future visual positioning system is discussed.

In summary, calibration objects can be roughly divided into monocular, binocular and multi-camera calibration. At present, there are many theories and methods for single-purpose calibration, with basically complete theoretical system, but the research on binocular and bi-objective method needs to be in-depth. Previously, researchers have proposed to apply artificial neural network to calibration, obtaining better calibration results. With the development of deep learning, it is possible that other excellent neural networks can also be combined with calibration to obtain more accurate results. In addition, all issues, such as how to solve the noise problem, exposure problem, accuracy problem and near-range and long-range calibration problems in the calibration process need to be considered in the future.

3. Image preprocessing

Image preprocessing refers to the need to perform operations such as noise reduction and image enhancement on the image before the formal processing of the image. Noise reduction is to eliminate noise in the original image through some filtering operations. Affected by internal and external factors such as illumination and industrial environment, the gray-scale contrast between the target and the background in the collected image may be insufficient, which will affect the subsequent image segmentation and edge detection. Therefore, it is necessary to enhance the collected images and improve the contrast of the images.

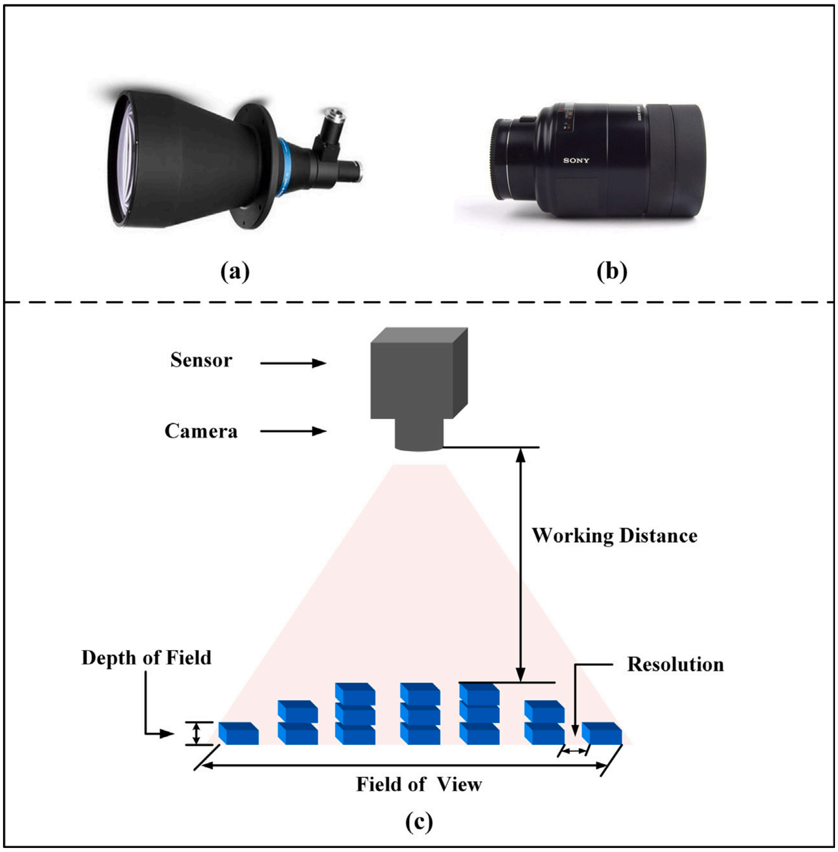


Fig. 5. Lens performance for positioning in machining (a) telecentric lens; (b) non-telecentric; (c) the lens parameters.

Table 2
Performance comparison of lens in visual positioning processing system.

Researcher, Year	Object	Parameters	Effects
Jing et al. [41], 2019	Object-side telecentric lens	4 times magnification, 0.1 degree telecentric angle, 0.3% distortion	Ensure the brightness consistency of the captured images
Zhang et al. [42], 2019	Double telecentric lens	80 mm depth of field, telecentricity less than 0.01 degree, 0.05% distortion	Achieved the purpose of double telecentricity, which can be applied to the positioning of large-size precision parts
Li et al. [46], 2018	Telecentric lens	40 mm depth of field, constant magnification ratio, low imaging distortion	High positioning accuracy with an average accuracy of 4.2 mm
Niu et al. [44], 2018	Double telecentric lens	Very small distortion, large degrees of freedom	Able to accurately locate the mirror object, the positioning error is less than 25 μm
Sun et al. [45], 2018	Double telecentric lens	The magnification is 0.057–0.5 x	Less than 0.51%, and the accuracy could meet the manufacturing requirements
Yang et al. [43], 2016	Achromatic objective	60 mm depth of field, 30 resolution	Suitable for positioning industrial parts, with good performance and application value

3.1. Image enhancement

Through image enhancement, the image quality can be improved and the features of the position of workpieces can be more prominent, so that the subsequent image features can be analyzed and identified. Image enhancement can be divided into three categories according to illumination conditions, namely, weak light, normal light, and strong light image enhancement. The light intensity of weak light is about 150 *lx*, that of the strong light is about 800 *lx*, and the light intensity between weak light and strong light is defined as normal light [57]. In addition, we have analyzed and discussed the image enhancement methods listed in Table 4. Han et al. [58] used a fast median filter algorithm to reduce image noise in order to obtain the information of the positioning hole in the incremental forming process of a car door. In the production of capacitive screen mobile phones, Huang et al. [59] enhanced the required image features using median filter to obtain the precise mark points, which is beneficial for subsequent positioning and processing. Since the median filter has good applicability only to single-layer impulse noise, Jiang et al. [60] proposed a new adaptive median filter method with stronger feasibility, which improved the image enhancement effect while suppressing multi-pulse noise. Therefore, the median filter is given priority to enhance the image in general.

Images and videos obtained under low light level conditions usually lose visibility and contrast seriously, which brings difficulties to subsequent image processing and analysis. Enhancement of low illumination images is one of the vital ways to solve the problem [61].

Table 3
Performance comparison of calibration algorithms used in machining positioning.

Classification	Researchers, Year	Methods	Performances	Remarks
Monocular	Chen et al. [51], 2021	Nine-dot, camera self-calibration	Anti-noise performance and higher accuracy than the fast calibration algorithm	Suitable for laser cutting, but the calibration effect in other machining is unknown.
Monocular	Fan et al. [52], 2021	Base frame calibration	Rotation and translation accuracy can reach 0.1 degree and 2 mm respectively	Real-time calculation, but this method needs to use two or more robotic arms at the same time.
Monocular	Wang et al. [53], 2020	Binocular ultra-wide angle long-wave infrared camera calibration	The average reprojection error and the root mean square are reduced to 0.23 pixels and 0.33 pixels, and the baseline length error is reduced from 1.00% to 0.23%.	Only calibrate for external parameters, and ignore the influence of internal parameters.
Monocular	Peng et al. [54], 2020	Kinematic calibration	Compared with the calibration result of the classic D-H kinematics model, the deviation is reduced by nearly 7 pixels, and the error is reduced by 87%.	Effectively avoid system errors caused by camera parameters in visual calibration, improve positioning accuracy, and have good economy and versatility.
Monocular	Wang et al. [50], 2017	An improved calibration algorithm	Significantly improve the chip positioning accuracy, with good stability and robustness	Need to rely on the error of each part of the visual positioning system; suitable for LED chip positioning system.
Monocular	Ding et al. [49], 2016	A calibration algorithm combined with artificial neural network.	Higher calibration accuracy and generalization ability than traditional calibration algorithms.	The algorithm idealizes the calibration model without considering the constraint relationship between parameters.
Binocular	Wan et al. [13], 2021	Eye-in-hand calibration	Provides an efficient way to enhance the positioning precision in rotation	Achieved a good positioning effect, but the calibration process is complicated.
Binocular	Jin et al. [55], 2019	Distortion correction	The measurement error is significantly reduced, and the maximum error is only 0.074 mm	The method is effective to improve the calibration accuracy, but it separates the camera calibration from the vision system.
Multi-camera	Chen et al. [56], 2019	An adaptive point cloud correction algorithm	Adaptable and effective to different types of static and dynamic targets of uncertain geometric changes and vibrations	Provides a theoretical basis for real-time target positioning and tracking, and further research is needed.

Feng et al. [62] proposed a dark channel enhancement method that adaptively increased the contrast of a given image. Experimental results showed that the method improved the brightness and contrast of traditional low-brightness images, also effectively suppressed the strong light area. Jiang et al. [63] found that images under low light have similar visual characteristics to blurred images.

Therefore, they utilized the defogging methods to improve the dark channel model and combined it with local smoothing and image Gaussian pyramid operators, which could effectively enhance the local details. However, this method cannot avoid noise amplification and color distortion in the images. Although the use of low-pass filtering and logarithmic transformation can eliminate the illumination component to enhance the images, it is impossible to avoid the halo phenomenon near strong edges [64]. Therefore, Park et al. [65] proposed a low-light image enhancement method based on the variational Retinex model using the bright channel prior and total-variation minimization, which estimates the brightness, intensity and reflectivity of light to control the amount of brightness enhancement. It turned out that the proposed method can provide better enhanced result in the sense of both better brightness enhancement and less undesired artifact. Zhang et al. [66] raised a low-illuminance image enhancement algorithm based on directional total variation Retinex, which obtained the final enhanced image by restoring the real color of the scene, illuminance image estimation and local brightness processing. Experiments certified that the algorithm had achieved significant effects in removing color deviation, enhancing details and suppressing artifacts. The images obtained under strong light conditions, whose color contrast is low and close to the background gray. According to the study by Li et al. [67], a convolutional neural network for weak illumination image enhancement algorithm was proposed, with the Retinex model, a convolutional neural network to estimate the illuminated image, and a guided filtering to optimize the illuminated image, indicating that the combination of Retinex model and convolutional network can get a better enhancement effect. Lu et al. [68] investigated a high light removal technology through improving the relationship of tone mapping, which realized the feature enhancement and extraction of low illumination region of metal parts.

In summary, scholars have proposed distinct schemes for image enhancement in different illumination (weak light, normal light and strong light). Under normal illumination, noise is one of the factors that affects image quality greatly. Hence, the median filter is often used to enhance images. While reducing noise, the filter does not blur the boundaries of the image, but also preserves the edge details well. Mean filtering and Gaussian filtering have the effect of suppressing noise, but they will destroy the edge information of the image and affect the subsequent processing of images. Wiener filtering can play a better smoothing effect in image restoration, but due to the difficulty of data conditions, it has not been widely used in applications. Due to low brightness and contrast of the images captured in weak light, which affects the subsequent image processing and causes the accuracy of positioning to decline or positioning failure. For the processing of weak light image, the Retinex algorithm is mostly adopted in literature to restore the real color of low illumination image and improve the accuracy of illumination estimation. However, the noise and artifacts in low illumination image will also be amplified during enhancement process. The improved Retinex algorithm can achieve better results, but a systematic theoretical system for the enhancement of images with low illumination areas has not yet formed.

3.2. Image segmentation

In the processing of machining positioning, the position of the workpieces (region of interest) is the focus of attention of researchers.

Table 4
Image enhancement methods for positioning under different illuminance.

Methods	Applicable scene	Strengths	Weakness
Median filtering [63]	Normal light(processing of automobile door, Sheet forming and manufacturing)	Effectively suppress noise	Good performance only for images containing a single layer of impulse noise
Adaptive median filter [64]	Normal light(Good shooting environment and no overexposure)	Efficient processing of noisy images	Unable to avoid image distortion problem
Retinex algorithm [65]	Weak light(unfocused beam, and dim working environment)	Effectively avoid distortion problems	A halo may appear near strong edges
Optimized Retinex algorithm [66]	Weak light(unfocused beam, and dim working environment)	Suppress noise more effectively and reduce distortion	The algorithm is more complicated
Dark channel enhancement [67]	Weak light(unfocused beam, and dim working environment)	Improve image contrast, effectively process strong light images	The images are easily over-enhanced
Low illumination enhancement [68]	Strong light(positioning cutting of metal parts)	Realize feature enhancement and extraction in low illumination areas	Only for high-gloss metal workpieces

In order to ensure the accuracy of positioning, it is necessary to separate the region of interest from images. Image segmentation is to use certain features (color, intensity, texture, etc.) of the target area to separate the target from the background [69]. Therefore, the quality of image segmentation directly affects the accuracy of workpieces positioning. Image segmentation methods from two main directions are summarized below: traditional segmentation methods (threshold segmentation, image segmentation based on edge detection, and region-based image segmentation) and image segmentation based on deep learning.

3.2.1. *Traditional image segmentation methods*

Threshold segmentation is a traditional image segmentation method. The basic principle is to select an appropriate threshold value and extract it from the background to highlight the target area through statistical calculation of the image gray level. Otsu is a more commonly used method. This method divides the image into two parts, the target and the background, according to the gray scale characteristics of the image. When the variance between the target and the background reaches the maximum, the segmentation effect is best. The Otsu is very sensitive to salt and pepper noise. When the collected image contains noise, the one-dimensional Otsu has a general segmentation effect. Therefore, researchers often use improved Otsu segmentation to obtain satisfactory results [70].

Yang et al. [71] improved the image segmentation for the dispensing machine of the visual positioning system, which obtained the center position of the segmented region via the Otsu methods and introduced the particle swarm optimization (PSO) algorithm to optimize the speed and accuracy of image segmentation for getting the best threshold. Experimental results showed that PSO algorithm can improve the speed and accuracy, reduce the effectiveness of the algorithm and meet the needs of dispensing. He et al. [72] considered the two-dimensional histogram to be more complicated, so an improved median filtering method was used to remove image noise; and the area-based Otsu [73] method was used to distinguish targets from the background. Lu et al. [74] improved the anti-noise ability and calculation speed by changing the coordinate system of the two-dimensional histogram. The improved two-dimensional Otsu method segmentation effect is significantly better than the one-dimensional Otsu method. Chen et al. [75] proposed an improved fast two-dimensional Otsu threshold segmentation method of gray-gradient two-dimensional histogram, which effectively accelerates the segmentation time from 2.5 s to 0.07 s. Zhou et al. [76] found that using the Otsu threshold segmentation method in the drilling process could not successfully locate the tool defect area. For tool image segmentation and wear area edge positioning, they proposed the Otsu segmentation method based on Laplacian edge information and the Canny operator edge detection method based on morphology. The new method has a measurement error of 6.04%, which can be effectively and applied to real-time positioning and monitoring of industrial tool wear. The threshold segmentation method is simple in principle and easy to implement. However, this method is ineffective when processing workpiece images that contain noise.

Image segmentation based on edge detection is a process of detecting the existence and position of edges formed by sharp changes in the color intensity (or brightness) of the images. The essence is to use a certain algorithm to extract the boundary between the object and the background in the image [77], and then analyze the characteristics of the target object. The core of edge detection is the choice of edge operators. The classic edge detection operators include gradient operators (Sobel, Prewitt, Robert operators, etc.), differential, (Kirsch operators), Laplacian, and canny operators. The geometric shape of the operator determines the most sensitive feature direction of the edge. The edge detection effect of several operators is shown in Fig. 6, which shows that the Canny operator has a complete and smooth effect. Li et al. [78] utilized Sobel operator and Hough transform to perform edge extraction and fitting(line and circle) to realize the positioning and segmentation of target objects (workpieces with meshed metal structure). In the process of porcelain polishing, Hosseininia et al. [79] used Sobel operator combined with morphological functions to improve edge detection accuracy. The method using the edge detection operator has a good effect on high-contrast image segmentation and can clearly segment different regions, but this method cannot obtain a continuous segmentation structure, and the edge-based segmentation method is extremely sensitive to noise. In order to improve the continuity problem of segmented regions, Yong et al. [80] proposed an image segmentation algorithm that combines regional similarity and edge discontinuity, and introduced a segmented gradient calculation method in the edge factor to obtain a more accurate Divide the boundary. The experimental results showed that the algorithm proposed in this paper can find the image segmentation boundary more accurately and improve the segmentation accuracy. The area-based image segmentation method is to segment the image according to the spatial information of the image, and classify the pixels based on the similarity characteristics of the pixels and form the area. Tang et al. [81] proposed an image segmentation method based on region merging. As a single-layer segmentation algorithm, the method avoids over-segmentation while preserving details. In summary, traditional image segmentation methods mostly use the surface information of the image and are suitable for single-shaped workpieces to be processed, but are not suitable for segmentation tasks that require a large amount of semantic information, and may not be able to cope with a large number of actual complex positioning and processing tasks.

In summary, image segmentation is an important step in image preprocessing. It is the main procedure to extract the attributes of the workpiece in the image, which is a prerequisite for the positioning processing. The most fundamental and commonly employed segmentation method is the threshold method, which directly selects an appropriate threshold for segmentation. The principle of this method is simple and

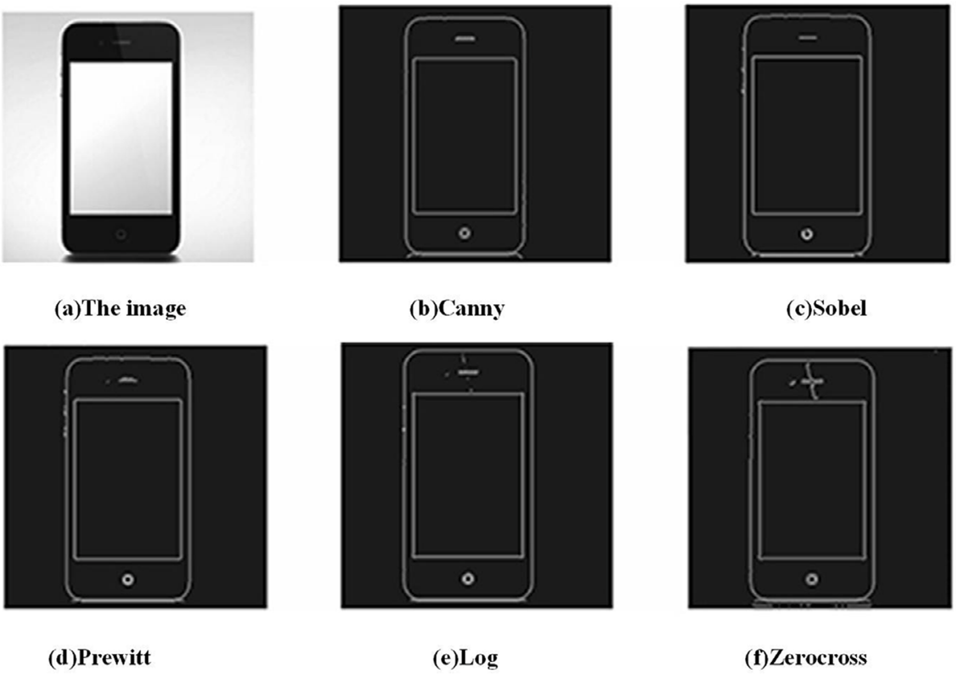


Fig. 6. Application effect of edge detection operator in positioning processing [9].

easy to implement. However, this method is not effective in processing noise-containing workpiece images. For image segmentation methods based on edge extraction, it is difficult to overcome the influence of noise by directly using gradient or differential operators. Therefore, the image must be smoothed and filtered before edge detection, and the segmentation effect is obviously better enhanced. Traditional image segmentation technology can yield excellent results using normal workpiece images (favorable shooting conditions and low noise). However, these traditional methods do not consider the calculation speed and segmentation accuracy simultaneously. Hence, a segmentation method that satisfies the requirements in terms of both positioning accuracy and operation speed must be developed. The research of image segmentation algorithms is the main hotspot for the image segmentation module.

3.2.2. Deep learning methods

Several image segmentation methods exist, but all these methods have a common problem—the tradeoff relationship between segmentation accuracy and anti-noise ability. With the development of deep learning, several excellent networks for image segmentation have been introduced. Compared with the traditional image segmentation methods (threshold-based segmentation, edge-based segmentation, etc.), the method based on neural networks is faster and more accurate, and is also applicable to complex-textured images.

Li et al. [82] used ConvNet for feature extraction and workpiece positioning. Experimental data confirmed that the ConvNet network can provide accurate positioning coordinates and that the final positioning accuracy after training can be as high as 97%. Wang et al. [83] applied convolutional neural networks (CNNs) to the positioning and classification of mechanical parts, combining multi-scale training, network pre-training, k-means dimensional clustering, and batch size setting methods based on CNNs. The experimental results showed that the method was robust and had an accuracy and positioning speed of 85.8% and 23 frames per second, respectively. In addition, it achieved a suitable balance between positioning accuracy and speed, and provided a basis for real-time positioning and processing of parts. Bai et al. [84] proposed a computer vision positioning algorithm based on a radial basis function (RBF) neural network combined with an improved Canny operator. This algorithm can realize sub-pixel positioning to solve the positioning problem of industrial robot on the production line. Experiments showed that the probability of positioning errors was less than 6%, and that the calculation time was less than 0.01 s.

Early neural networks were only used to extract image features. The emergence of fully convolutional networks (FCN) introduced new solutions to the field of image segmentation (end-to-end training methods). Ghose et al. [85] described the impact of deep learning on the field of image segmentation and laid the foundation for its application in machining positioning. To overcome the shortcomings of current traditional image segmentation, Li et al. [86] also proposed a laser image segmentation method based on deep learning which used wavelet transform to extract features of laser images and trained laser image feature vectors with introduced artificial intelligence learning algorithms, which classified the laser image pixels according to the training results, so as to realize the laser image segmentation, showing that the accuracy of this deep learning algorithm for laser image segmentation with and without noise is 91% and 95%, respectively, with significantly higher accuracy than that of classic laser image segmentation methods. Zhang et al. [87] started the study from mainstream image segmentation networks (FCN, SegNet, Generative adversarial network (GAN), U-Net), and discussed the methods of processing image segmentation, as well as its development. Wang et al. [88] proposed a new method for target tracking with FCN, which conducted deeply on off-line features and image set classification tasks according to massive image data, suggesting that this method can significantly improve the tracking accuracy. Aiming at the problems of inaccurate segmentation methods based on traditional machine learning, loss of edge information and robustness to be improved, Guo et al. [89] pointed out an image segmentation algorithm based on an improved fully convolutional neural network, which combines the deep learning model's better feature extraction ability and the sensitivity of clustering segmentation to edge information, and further uses the normalized cuts algorithm to assist segmentation, with the experimental results showing that the algorithm finally achieves a higher segmentation accuracy than the traditional convolutional neural network image segmentation algorithm. Taylor et al. [90] discussed the common deep network architectures (AlexNet, Visual Geometry Group (VGG), Google inception Net (GoogleNet), Residential Networking (ResNet), Recurrent neural Network (ReNet)) in image segmentation, and pointed out the development trend of image segmentation technology in the future. A comprehensive performance comparison of key image segmentation methods (traditional and deep learning segmentation methods) in terms of positioning processing is presented in Table 5.

3.3. Summary

Under the influence of machining environment and shooting equipment, image enhancement can be divided into three types of enhancement: weak light, normal light, and strong light. There is a relatively complete set of processing modes for the research of image enhancement under normal illumination. In recent years, researchers have made more in-depth research on low-illuminance image enhancement techniques, but existing enhancement methods (dehazing models and Retinex's theory) ignore the influence of noise on image quality during image processing. Enhancement in low illumination conditions requires consideration not only of brightness and contrast, but also of noise and equalization. Therefore, developing a mature and practical low illumination enhancement system remains a major challenge. It is worth mentioning that the convolutional neural network has relatively large anti-interference ability, so combining convolutional neural network with existing models and theories to overcome the noise problem is a direction worthy of further research. In addition, there are currently few image enhancement methods under strong light conditions, which is another major task in the future.

Image segmentation is one of the important steps of image preprocessing. Extracting the properties of the workpiece in the image is the main step and the premise of the positioning process. At present, the research on image segmentation can be roughly divided into two categories: one is the traditional segmentation and the other is the deep learning segmentation. The traditional segmentation mainly include: threshold-based image segmentation methods, edge-based image segmentation methods, and region-based image segmentation methods, with simple and easy operated principles, which are sensitive to noise. When the image contains noise, the segmentation effect is poor. The deep learning segmentation mainly includes cluster analysis image segmentation and neural network-based image segmentation methods, which can solve the problem of noise sensitivity in the traditional methods and greatly improve the segmentation accuracy. With the rapid development of artificial intelligence technology, training data tends to be quantified. Traditional image segmentation methods will gradually be replaced by segmentation methods based on deep learning. The existing segmentation algorithm technology based on deep learning is relatively mature, but there are problems such as large amount of calculation and long time-consuming. On the other hand, image segmentation technology is often oriented to a specific application field, and better results can be obtained by combining with related field knowledge. The application of image segmentation technology based on deep learning in industrial positioning processing will become more and more common in the future. In addition, a set of image segmentation methods with universal applicability is the direction of future research efforts.

4. Feature extraction for processing positioning

4.1. Traditional methods

Feature extraction is the basic premise for locating processing objects. Feature extraction is a process of dimension reduction and is a basic computational task in machine vision [98]. Traditional feature extraction technology generally extracts the edges, points, textures, etc. of the object to be processed in processing positioning. Representative feature extraction algorithms include SIFT, SURF, and so on.

For improving the cutting accuracy of the automatic cutting machine, Li et al. [99] proposed a method with machine vision, which used an improved morphological gradient filter operator to find the rough edge of the sheet, and the least square method to fit the sub-pixel edge points that met the requirements into a straight line, and finally the sheet offset was calculated according to the geometric relationship to correct the deviation, performing the position by extracting feature points, with the positioning accuracy theoretically reaching 0.03 mm. However, the visual positioning method is not stable in actual working conditions due to its influence on the working environment. Yang et al. [100] proposed speeded up robust features (SURF), an image feature detection method based on the Gaussian pyramid model; SURF replaces the Gaussian filter in scale-invariant feature transform (SIFT) with a square filter and analyzes the image at different resolutions to obtain differential images in different scale spaces. The authors found that the speed of feature extraction increased by 75% when using SURF. The SURF [101] algorithm – an accelerated version of the SIFT – uses integral images and box filters to reduce computational complexity while maintaining an accuracy similar accuracy to that of SIFT. Chen et al. [102] proposed an improved template matching method that uses the pyramid hierarchical search strategy to improve the speed of feature search and extraction for positioning and dicing of semiconductor chips in an automatic dicing saw. Rajaraman et al. [103] combined computer vision positioning technology with robotic welding, extracted features from the CAD model, and matched and positioned extracted features. After comparison and verification, it was found that the visual positioning welding system was 85% faster. Wei et al. [104] proposed a new method that selects the shape features of the workpieces through attribute reduction and generates rules based on the recognition knowledge to classify workpieces instantly and accurately. Experimental results showed that the recognition rate of the sample could reach 100%. However, this method requires a large amount of feature data. The limited number of samples taken by the camera could not meet the needs of this method. Traditional feature extraction algorithms have poor performance, and when using traditional methods to locate relatively smooth artifacts (such as arcs, circles, etc.), unable to extract too many feature points may directly cause inaccurate positioning.

4.2. Template matching algorithms

Template matching is one of the most commonly used methods to locate a target location, which can traverse the image through a sliding window and calculate the similar value between the sliding window and the image template to determine the location of the matching template. In the visual positioning system, it is one of the commonly used methods to locate the target position by detecting the edge contour and using template matching. Fast and accurate matching method is the key to high-precision positioning. In order to shorten the matching time, Tian et al. [105] improved the traditional method by reducing the matching points, and proposed a fast template matching method based on image edges. This method finds out the representative edge information by binarizing the template graph, and then matches the points corresponding to the features. When the absolute difference of the feature points exceeds a certain threshold, the calculation is skipped and the next detection is performed. Experiments show that the matching time of the template size of 224 × 224 was 0.4 s faster than the matching time of the 11 × 11 template. Obviously, this method was better for matching large templates. Aiming at the problems of long calculation time of existing target matching algorithms and inaccurate positioning of rotating and zooming targets, Yu et al. [106] proposed a spiral target matching algorithm based on pyramid image structure and Hu moments. Experiments showed that the matching method proposed had higher positioning accuracy and anti-jamming characteristics for spiral targets with variable rotation and position. However, the algorithm is only applicable to workpieces with complete contours, and cannot be applied to objects with incomplete and discontinuous contours. For large-size workpieces whose size exceeds the FOV of the camera, image stitching must be performed to achieve detection and

Table 5
Classification of image segmentation algorithms for visional positioning.

Classification	Method	Object	Performances	Remarks
Traditional segmentation methods	Otsu [71]	Semiconductor encapsulation	Otsu combined with particle swarm algorithm optimized the segmentation speed and accuracy of grayscale images, and met real-time requirements.	Although the optimal threshold can be obtained, it is sensitive to noise and can only be segmented for a single target.
	Two-dimension Otsu [70]	The tubular Workpieces	Change the coordinate system of the two-dimensional histogram to enhance the noise resistance and increase the calculation speed.	The anti-noise ability of the Otsu algorithm is enhanced, but it takes up a lot of storage space during calculations, and the results are not accurate enough.
	Three-dimension Otsu [91]	The color workpieces	Better preserve tiny details and boundaries, and reduce execution time.	Solved the technical shortcomings of one-dimensional and two-dimensional Otsu and provided the best threshold for multi-level threshold processing, but the method has not been further verified.
	The iterative method [69]	The color workpieces	Better preserve tiny details and boundaries, and reduce execution time.	Solved the technical shortcomings of one-dimensional and two-dimensional Otsu and provided the best threshold for multi-level threshold processing, but the method has not been further verified.
	Canny operator [9]	The fillet workpieces	Obtain images with clear edges and can effectively suppress noise.	The theory of Canny operator edge detection is relatively complete, but the shape of the detection workpiece is limited.
	LOG [92]	Glass shards	Less calculation, high efficiency of edge detection.	The combination of LOG operator and mathematical morphology improves the anti-noise ability, but the algorithm is not universal.
Deep learning methods	CNNs [86]	Laser processing	For noisy and no-noise laser images, the segmentation accuracy reached 91% and 95%.	Methods based on deep learning should be verified in various fields.
	Fast R-CNN [93]	Laser welding	Effectively separate the detection target from the background and eliminate noise interference. The maximum error is 0.47 mm, and the average error is 0.29 mm.	Suitable for welding robots and can work in complex environments, but it is unknown whether the welding accuracy can be achieved in precision machining.
	Mask R-CNN [94]	Specific data set (BIWI)	Tested on the BIWI data set and self-generated data set, the accuracy rate reached 83%.	Good positioning results for groups and individuals, and may be applied to mechanical positioning processing in the future.
	ConvNet [82]	Automatic positioning and placement of workpieces	The system achieved a 100% success rate in 200 workpiece placement tasks and be completed within 60 s; the average time for precise positioning and placement is less than 20 s.	Good performance in accuracy and speed, but the model performs poorly under weak light conditions.
	FCN [89]	Specific data set (VOC2011)	Accuracy up to 94%,and precision up to 95%.	Process workpiece images of any size, with better segmentation results.It can be applied in the field of machining positioning in the future.
Others	K-means [95]	Car tires	100 samples were tested, the scoring accuracy rate was 95%, and the conformity assessment accuracy rate was 99%. And the average integrity calculation time is 9.27 ms.	It is of guiding significance to the automotive industry and should be verified in practical applications later.
	Spatial clustering [96]	Workpieces with discontinuous edges	Good continuity, connectivity between the areas, and the boundary description is relatively accurate.	Solved the problem of regional similarity and edge discontinuity, but the calculation time increases accordingly.
	GA [97]	Theoretical research	Reduce the complexity of the problem and obtain a faster convergence speed.	A segmentation method combining GA algorithm and ANNs was proposed, but no specific verification test was carried out.

positioning [107], the principle is shown in Fig. 7. Chen et al. [108] proposed an improved template matching method based on the initial angle, which can establish an image pyramid structure with a pyramid hierarchical search strategy, improving the search speed of feature images. The experimental results show that the improved algorithm can match almost all targets to achieve precise positioning and real-time cutting with a 99.25% success rate, even in the conditions of low light, strong light, uneven illumination and angle rotation. The above feature-based algorithms can match targets by searching for line, corner and contour features, which are adaptable and robust. Although the combination of template matching and some improved algorithms can improve the matching accuracy, the complex and time-consuming problem of extracting and analyzing geometric features still cannot be solved. Therefore, it is one of the future tasks to explore the template matching algorithm with low-time consuming and high precision.

4.3. Deep learning methods

In recent years, computer vision methods based on deep learning have developed rapidly. Feature extraction has been widely used in many fields. It is used to find all the objects of interest in the image and determine their positions and sizes [101]. Compared with traditional local feature description methods, deep learning is a self-learning feature extraction method, and the obtained features can describe the rich information of an image more clearly [109]. Therefore, the application of deep learning to extract representative features has received extensive attention.

Deep learning methods based on CNNs have received widespread attention in the context of target detection and processing positioning. The depth feature extraction model is depicted in Fig. 8. Fast R-CNN, Radial basis function(RBF), Single shot multibox detector(SSD), and other algorithms have been introduced, and they constitute the basic framework of target detection. Deep learning requires a large number of data sets, which are used in image target detection and feature extraction after training. In target detection, traditional detection methods are considerably affected by noise and cannot detect true and complete contour edges. Methods based on deep learning can be directly applied to noisy images. The advantage of these methods is that they require neither retraining nor re-adjustment of the threshold parameters. Therefore, these detection method have been extensively. Zhang et al. [110] proposed a part recognition method based on deep learning, using 300 training samples and training the recognition model over 1000 iterations. Experiments showed that the model could extract the shallow and complex features of parts automatically and that the recognition accuracy was as high as 98%. However, due to the small number of parts and samples, the generalization ability of the model was weak. Zhang et al. [111] proposed the application of deep learning in monitoring laser processing, using two typical CNN models (AlexNet and ResNet). The results showed that the multi-task learning performance of AlexNet is significantly better than that of ResNet. In summary, feature extraction methods based on deep learning are self-adaptable, self-learning, fast and highly accurate. Their main advantages are strong execution, high accuracy, strong robustness, and insusceptibility to influences. Tian et al. [112] proposed a new convolutional neural network algorithm, which introduces the recurrent neural network into the convolutional neural network, and uses the two types of networks to learn image features in parallel, which improves the accuracy of feature extraction and image recognition capabilities. This method can be used for feature extraction of complex images and backgrounds.

In recent years, feature descriptor methods based on deep learning (HardNet, HyNet, Smart ocean under water sensor network (SOSNet), etc.) have been proposed one after another. Huo et al. [113] proposed a straight line feature description method based on convolutional neural network learning, which used about 208,000 matching straight line pairs for training, and performed feature extraction through the HardNet network structure and triple loss function, showing that this method has good distinguish ability under the conditions of viewing angle, blur, scale and rotation. However, the proposed method is more friendly to objects with more linear features, so whether it can be applied to machining positioning requires further verification. In terms of target detection in hyper scale space, Zheng et al. [114] proposed a HyNet detection framework, which provided a new perspective for the representation of scale-invariant features, but it will bring additional computational burden to HyNet for very large-scale feature learning. In future, a more efficient super-scale feature learning algorithm should be developed. Durrani et al. [115] proposed to apply SOSNet to underwater sensor detection with the experiments which has proved that the performance of this method is better than particle swarm optimization, ant colony algorithm and gray wolf optimization algorithm. However, whether the algorithm can be used in machining location has not been verified. Wen et al. [116] proposed a convolutional neural network model based on dual convolutional channels, which was compared with the current mainstream positioning algorithms, with the results showing that the algorithm has higher positioning accuracy and success rate, but has not been verified in positioning processing applications. Table 6 summarizes some of the feature extraction algorithms (traditional and deep learning algorithms) used in visual positioning in processing.

4.4. Summary

The application of feature extraction algorithms in machining positioning can be roughly divided into four categories: traditional feature extraction algorithms, template matching algorithms, deep learning algorithms, and other algorithms. In this study, the most commonly used traditional feature extraction algorithms, template matching algorithms, and deep learning-based algorithms are described in detail. Feature extraction algorithms for visual positioning in machining are shown in Table 6.

Traditional image feature extraction methods include SIFT, SURF and so on, which have satisfactory invariance in rotation, affine transformation and illumination changes. These methods are usually used for object recognition and image matching, mainly relying on spatial information (shape features, edge features, corner features, etc.). If the image is blurry and the features of the workpiece are not obvious, a good positioning effect cannot be achieved. The core of template matching algorithm, simple and easy to use, is mathematical algorithm. All these methods mentioned above are very mature in theory, adaptable, robust, easy to implement and fast, but take a long time to extract and analyze image features with complex geometric shapes and backgrounds. In addition, the template matching method requires a high degree of consistency in size and angle between template and target image, with weak anti-interference ability. The feature extraction method based on deep learning can effectively avoid the shortcomings of traditional algorithms, reduce the impact of noise and environmental variables, with a wide range of applications and strong stability, which can effectively improve the accuracy and quality of feature extraction.

The latest descriptor methods, such as HyNet, SOSNet, HardNet, etc., appeared in recent years have been proved to have good performance, but there are few literatures mentioning its application in machining positioning due to the novelty of this method, with the phenomena of illumination changes, deformation, disappearance, background confusion, and scale changes in actual images. Therefore, researchers should consider comprehensively improving the diversity of training models based on deep learning.

5. Case studies

5.1. Application in traditional machining

In machining, exact positioning and processing of workpieces are important to ensure product quality. In terms of non-contact positioning, machine vision has several advantages compared with traditional manual positioning; these include high precision and satisfactory real-time performance. The traditional positioning method, which involves the use of a contact measuring instrument and measuring head [127], is used for manual workpiece positioning, and the qualified rate is ensured through general examination and sampling inspection by humans. This often leads to low production efficiency because of environmental and human-related factors. Visual positioning methods can locate critically as well as measure and evaluate the surface quality of workpieces in real time, and can improve the product qualification rate. Thus, they can address the shortcomings of traditional positioning methods.

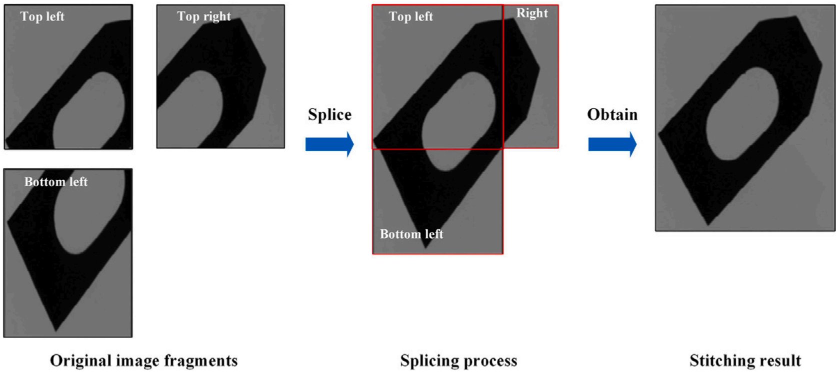


Fig. 7. Positioning of large size workpieces [107].

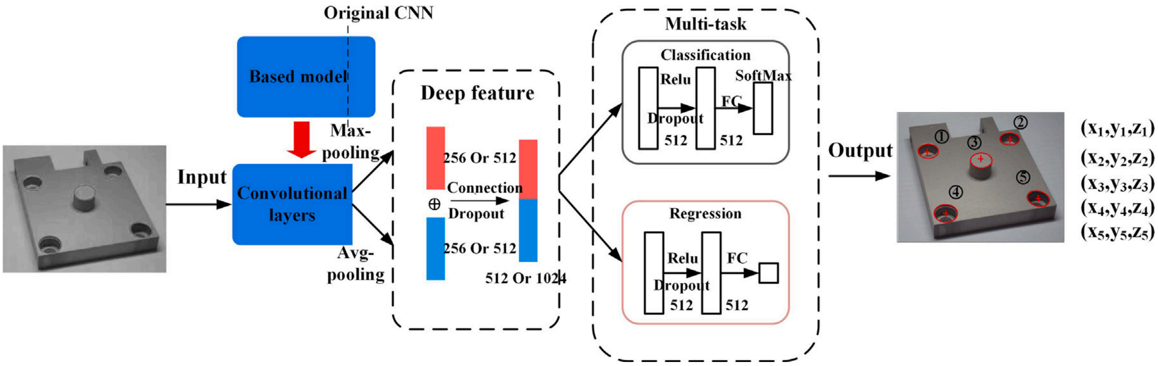


Fig. 8. A typical deep feature extraction model in machining for positioning.

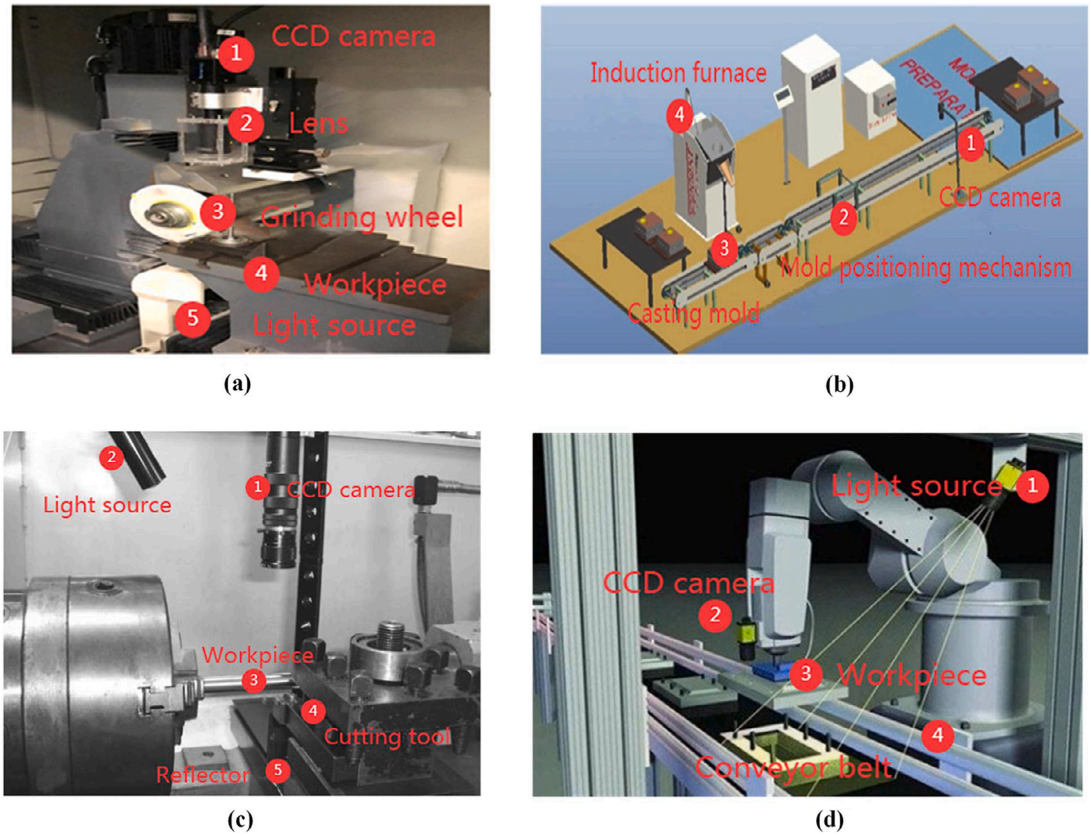


Fig. 9. Typical application of positioning system (a) grinding [124]; (b) casting [125]; (c) turning [126]; (d) drilling [24].

Table 6
Feature extraction algorithms for visual positioning in machining.

Classification	Methods	Object	Characteristic	Remarks
Traditional methods	SIFT [117]	Workpieces with clear contours and many feature points	Maintain good invariance to image geometry and optical deformation	Large amount of calculation,inaccurate positioning of workpieces with few fuzzy edge feature points.
	SURT [118]	Regularly shaped workpieces (such as square and round workpieces)	Stable matching effect and high matching accuracy	Improved the situation of false matches, but the algorithm takes a long time.
	HOG [119]	Workpieces with simple shapes (shaft workpieces, plates, workpieces with holes, etc.)	Effectively preserve the edge details of the image.	Large amount of calculation, unable to process occluded workpiece images.
	ANNs [120]	Rolling element bearings	The accuracy of the trained neural network model in the training data can reach 90.2%.	High accuracy cannot be obtained when the background feature is similar to the target feature
Template matching methods	Improved template matching method [105]	Workpieces with continuous edges	The matching time of the 224 × 224 template size is 0.4 s faster than the matching time of the 11 × 11 template.	Use large size templates, which may not be suitable for small workpieces.
	Shape matching [14]	Casting workpieces	System repeatability is within 2 mm.	Provided a way for the positioning and grasping of rough-machined castings, but its accuracy needs to be improved.
	Template splicing [17]	The large size workpieces	Solve the positioning problem of large-size workpieces; faster than traditional template matching.	The Images can be stitched if they have at least 30% overlap, and the positioning accuracy needs to be improved.
Deep learning methods	Improved CNNs [64]	Unfeatured Weld Positioning	Provided a solution for feature extraction of featureless images.	The algorithm has certain feasibility, but its performance needs further research.
	R-CNN [121]	Positioning of industrial robots (bottles)	Locate and recognize targets with a recognition accuracy of 82.34% in a complex environment.	Provide an experimental reference for the application and development of industrial robots, but the positioning accuracy and precision need to be further improved.
	Improved SSD [73]	Unmanned driving field	Taking into account the problem of multi-scale fusion, the feature map has richer semantics, and the detection accuracy is improved than that of a single SSD.	Validate the algorithm in a specific data set and not apply it in actual positioning.
	RBF [122]	Car body positioning on the production line	The translation error of positioning is less than 0.052 pixels, and the proportion error is less than 0.06.	Achieve sub-pixel positioning and can be developed in the automotive industry.
	SOSNet [115]	Location detection in water	Better superiority than GWO, PSO and ACO algorithm.	Has excellent detection and positioning capabilities, which can be verified in other positioning fields.
Others	Ant colony optimization [123]	Wheel alignment	Combine the advantages of gradient strength and phase consistency.	Parameters need to be set and the convergence speed is slow and time-consuming. The method needs improvement.

At present, the application of computer vision in machining is mainly focused on the positioning measurement, surface quality detection, and positioning processing. Before the start of the machining process, the original parts need to be initially positioned, which requires a long time. Mendikute et al. [125] proposed a new automatic alignment scheme based on three-dimensional vision technology, which utilizes automatic geometric coding and alignment algorithms to achieve automatic measurement calculation and virtual alignment and positioning of target on the representative point (surface to be processed). Experimental results showed that the overall precision of the scheme was 3 to 5 mm for parts with a length of 5 m. Abdul-Ameer et al. [126] developed a vision-based sensing system that provides information about the quality of the workpiece during processing and adjusts the processing parameters to process the visual feedback information. In addition, a computer program was developed for adaptive control of workpiece processing in real time. Visual positioning can also be used to improve machining accuracy during grinding, turning, and milling [128]. CNN systems with the vision positioning function have become valuable for machine tool intelligence because vision positioning represents a fast-growing intelligent feature for machines. Xu et al. [124] developed a novel vision-oriented open CNC (profile grinding machines) system (Fig. 9) for the precise machining of parts with contour surfaces (complex molds and cutting tools). The machining results indicated that the system can effectively combine image processing with motion control and improved machining precision in profile grinding. The specific processing flow and effect are shown in Fig. 10. Butt et al. [129] suggested a new automation scheme in the sand casting process; it involves the use of mold positioning technology based on computer vision algorithms to find the coordinates of the center of the inverted cup and then place the mold in the best position for precise pouring of the molten metal. The automation system

(Fig. 9(b)), once started, does not require any intervention or manual adjustment, which substantially improves production efficiency and accuracy. Post-manufacturing quality inspection is also an important process. Ou et al. [130] developed a machine vision recognition and positioning technique that can help robots to automatically recognize and accurately position smart meters in complex industrial environments. The method involves determining the center position of four screws, through image preprocessing and calculated of the contour of the meter based on the geometric position; then, the position of the meter is accurately determined using a positioning algorithm. Experiments revealed that the algorithm had practical value. Shahab [131] et al. developed a vision system (Fig. 9(c)) to locate machined parts. The machining accuracy was 10% higher than that of traditional turning machining. In addition, experiments showed that manufacturing of workpieces using computer vision is also suitable for grinding, milling, and other types of processing. Wang et al. [24] designed a rim valve hole positioning processing system (Fig. 9(d)) according to the characteristics of valve holes and the structure of the rim for measuring and positioning of the edge valve hole on the coating line. The system calculates the position of the rim hole and performs feature recognition and measurement through image processing to control the servo motor to locate the position of the wheel hole. The accuracy and reliability of the method were verified through experiments.

5.2. Application in non-traditional processing

With increasingly stricter requirements for machining accuracy and surface quality, traditional machining methods are no longer suitable for the difficult-to-machine materials and precision parts, such as stainless steel, heat-resistant steel, and titanium alloys. Non-traditional machining methods, such as electric discharge machining (EDM), laser machining, ultrasonic machining, and water jet machining have emerged. However, the machining accuracy of these methods is limited by several factors, such as suitable positioning of the workpiece during machining process to avoid damage. The combination of machine vision technology and special processing technology is expect to represent another breakthrough in the manufacturing industry.

An important precondition for an effective machining process is to ensure that the machining position is correct. In EDM, wire bending is one of the main factors that affect the machining accuracy. Dauw [133] proposed the use of an optical detector to detect and compensate for wire deflection in real time, for positioning and control during high-precision EDM cutting online. The processing efficiency was significantly improved in comparison with that of the traditional cutting machine. Huang et al. [132] proposed a novel method (a detection line algorithm) and established an EDM positioning and detection platform (Fig. 11(a)) that can detect the depth of drilling holes while effectively positioning the machining system. This system can provide a meaningful reference for EDM industry. In laser processing, accurate beam positioning is particularly important because of the small laser spot. Dorsch [134] developed a sensor system that can determined the correction values between the set and actual positions from measurements, this ensure that the laser welder can subsequently perform the welding in the correct position. To improve the productivity, Ho et al. [135] proposed a new method to orient the center position of the hole and monitor the laser drilling process using a computer vision system that can estimate the depth of the hole online. The use of high-power laser beams to ablate holes through workpieces is an important development in machining. Therefore, this method has the potential to reduce manufacturing costs. Defective workpieces can be produced in laser processing because of incorrect positioning or improper preparation of the geometric shape of component edges. Luo et al. [136] developed a seam-tracking system based on visual positioning that can locate the initial welding point and calibrate it automatically. For lap welding of titanium alloy (V-groove, fillet), the accuracy achieved was within 0.4 mm. Jia et al. [3] used positioning and navigation systems based on machine vision in laser micro hole machining. These systems mainly captured images of the micro hole using a CCD camera and navigated to the top of the micro hole, processed the collected image, and located the micro hole with a diameter of less than 0.3 mm. The system, shown in Fig. 11(b), can position circular holes accurately but is not as effective for the positioning of inclined, square, and other irregularly shaped holes. Computer vision technology can contribute to electrochemical machining and water jet machining as well [137].

In summary, using computer vision technology is widely used for positioning and detection in traditional processing but not as much in special processing. However, based on the foregoing discussion, visual positioning and visual inspection are expected to replace traditional methods in special processing.

5.3. Application in PCB machining

PCB is the foundation of the information industry, with PCBs existing in almost all products related to electronic information. With the rapid development of the electronic processing industry, PCB gradually tends to be miniaturized. The precise positioning of PCBs is a very important task for automatic assembly and inspection in the manufacturing process, which ensures the successful insertion of electronic components and the correct installation of integrated circuit chips on the board, to maintain the quality of electronic products. In addition, the automatic positioning of PCB can solve various subjective problems when manual positioning, which can quickly provide accurate size and position information.

In the past, PCB required complicated clamping adjustments to ensure the position consistency of the machine tool coordinate system and the file coordinate system during processing, with complicated steps, long operation time and low efficiency. As the development of visual positioning technology, many scholars have explored PCB positioning methods. Malge et al. [138] used visual positioning technology to locate and classify the defects on the PCB, and achieved good classification results. However, they did not consider the impact of noise on positioning. Kuo et al. [139] proposed an automatic marking point positioning method for PCBs based on template matching technology, which used artificial neural networks and combined moments of Hu and Zernike for training to extract feature vectors that are robust to rotation changes and scale changes, indicating that the positioning time of the proposed method is only 0.55 s, which is better than the 3.97 s of traditional global template matching. However, this automatic positioning method requires a series of complex pre-image processing operations and a lot of preparation work. The above methods are suitable for PCB positioning and defect detection, and the positioning objects have certain limitations. Wang et al. [140] proposed a positioning method to locate a chip; this method uses a deformable template to detect the deflection angle and offset in the process of surface mounting. It combines the gradient, gray, and geometric features of the image and identifies the best matching position between the deformation template and the target image through genetic algorithm optimization. Experimental results showed that the method is accurate and stability and has a high calculation speed. Moreover, its detection and rotation errors are less than 0.25 pixels and 1 degree, respectively, which fully satisfy the positioning accuracy requirements of the placement computer vision systems. Tsai et al. [141] proposed a fast image alignment method based on expectation maximization technology. Experiments demonstrated that the method can achieve PCB positioning with a translation error of less than 1 pixel and a rotation error of less than 1 degree. The above methods are suitable for PCB positioning and defect detection, and the positioning objects have certain limitations. Chou et al. [142] explored the application of deep learning technology in PCB positioning, and evaluated and compared four deep neural network models in PCB positioning performance. The data obtained in the experiments showed that the model combining CNN and support vector regression had the best estimation accuracy,

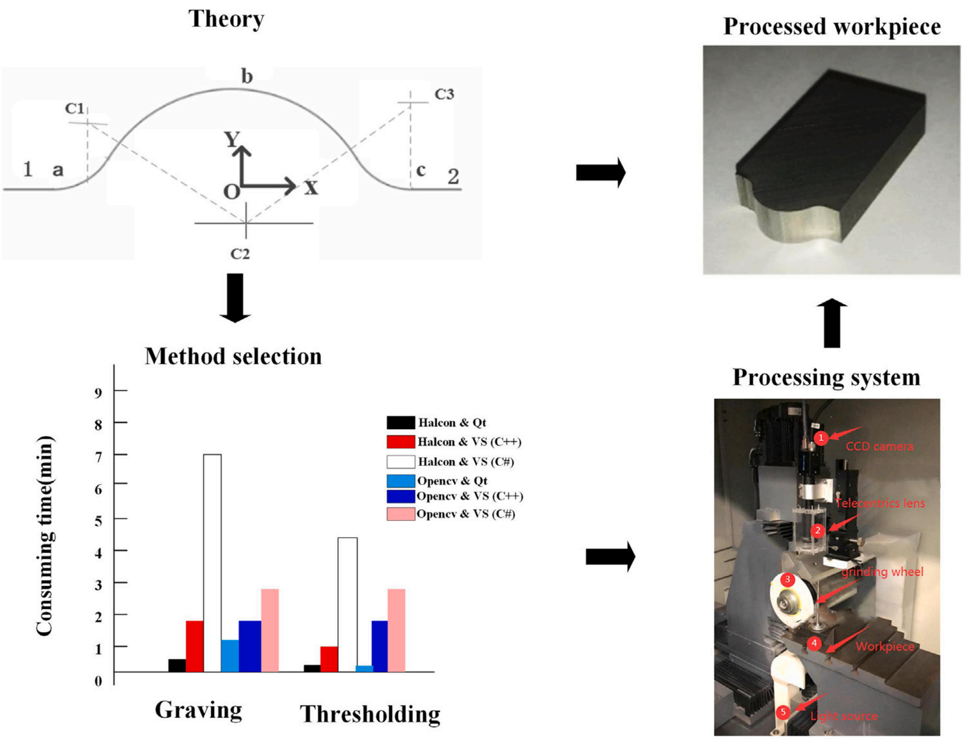
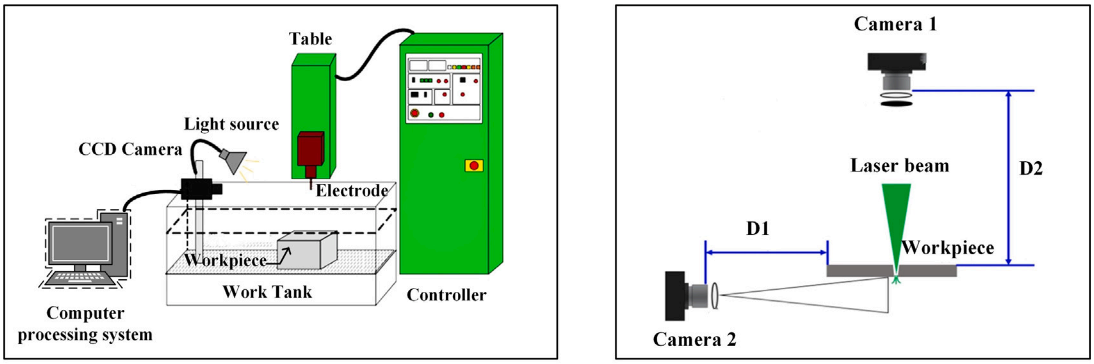


Fig. 10. The workpieces positioning of the grinding processing system [128].



(a)

(b)

Fig. 11. Typical application of positioning system in special processing (a) EDM vision system [132]; (b) laser drilling vision system [3].

with a maximum error of less than 1 pixel. Although the neural network model combined with the support vector regression machine can obtain good positioning results, this type of model is easily affected by changes in illumination. If the illumination cannot be controlled, the model will not show good results. Therefore, a fixed lighting device with the intensity of good light and stable light is the direction that PCB positioning system needs to focus on.

5.4. Summary

In summary, machine vision positioning technology has shown great potential in traditional machining (turning, milling, planing, grinding, drilling, etc.), non-traditional machining and PCB fields. Before the development of visual positioning technology, technicians often used manual or mechanical positioning to locate the workpieces to be machined, which is affected by subjective factors. The positioning effect is poor; and the accuracy is low. What is more, long-term operation can also cause damage to the operator. Compared with the traditional method (processing after manual positioning), determining the position of the workpiece using visual positioning technology and then performing accurate processing is significantly advantageous in terms of accuracy and efficiency, its effect can be shown in Table 7.

With the development of positioning algorithms and artificial intelligence, computer vision is widely applicable in machining. The initial positioning and machine alignment of the original parts before processing effectively reduces the preparation time before processing. In processing, the visual system is used for information feedback to determine the position of the workpieces and perform high-precision operations, such as cutting, welding, and drilling. For finished products, computer vision can be used to perform quality inspection to improve the efficiency of the entire processing system. In summary, incorporating computer vision components into CNC equipment can improve the automation and intelligence of the system. However, the visual system also has certain limitations. For example, an optimal lighting scheme is yet to be developed, and a method to further optimize the image processing algorithm is necessary. These problems must be solved through future research. In addition, visual positioning technology is also widely used in PCB processing (cutting, drilling, welding, etc.). A

Table 7
Summarization before and after using the visual positioning system.

Application scenario	Objects	Before using machine vision	After using machine vision	Effect
Traditional machining	Positioning (rim valve hole) [24]	Use visual observation to observe the position of the valve hole, which is labor intensive and low in production efficiency.	Automatically identify and locate valve hole.	The absolute error of the valve hole center location can be guaranteed within the error range of 3 mm.
	Grinding (parts with contour surfaces) [127]	Unable to intuitively detect and compensate contour errors during the machining process.	Meet efficiency requirements and improve the machining accuracy of contour grinding through combining image processing and motion control .	The average relative contour error was less than 3 μm compared with the in situ measurement.
	Milling (raw part) [128]	The massive consumption of labor and machine time; alignment accuracy exceeds acceptable range of 3–5 mm.	Lower human labor required;automatic photogrammetric calculations and virtual alignment.	Reduce time consumption and improve accuracy; the measurement error is below 0.1 mm.
Special processing	laser-electrochemical micro-hole [3]	Artificial observation has a low-accuracy positioning and a large amount of asymmetric micro-holes are produced.	Solve the positioning problem of the electrode wire and the micro-hole and improve the processing accuracy and efficiency.	The average distance error of measured and standard values in image coordinate system was 2.1 pixels, and the error was less than 0.012 mm.
	Laser-drilling process [135]	Unable to locate and monitor the laser drilling process online.	On-line image acquisition and analysis. Locate the position of the laser hole in real time and monitor the depth of the hole.	Verify the feasibility of monitoring the focus position and taper of the hole during laser processing.
	Laser welding [136]	The high reflectivity of the laser seriously affects the accuracy of positioning.	Accurately track the position of the weld through vision system, and improve the welding efficiency.	Tracking V-groove, fillet, lap and butt joints of titanium alloys with high accuracy of less than 0.4 mm.
PCB machining	Template matching positioning [139]	Time-consuming, low-precision, and cannot adapt to rotation and scale changes.	Sub-pixel level high accuracy and short computing time.	The average positioning time increased from 3.98 s to 0.55 s. The overall average error value is less than 7 μm, and error standard deviation is $1-3$ μm.
	Deep learning [142]	Time consuming and need complicated fitting algorithms to improve the estimation accuracy.	Realize real-time high-precision positioning and have better robustness.	Achieve a sub-pixel accuracy and yield a rotation error less than 1 degree with 1-millisecond evaluation time.

positioning processing system suitable for various fields and industries will become the unremitting pursuit of researchers.

6. Outlook

In recent years, with the rapid development of image processing algorithms and the widespread adoption of automation in production, computer vision technology has received increasing attention. Visual positioning technology has also been widely used in mechanical processing. However, due to the diversity of workpiece shapes, the complexity of machining environments, and the difference between theoretical and practical situations, visual positioning technology needs to be further improved. In this regard, future research should focus on the following aspects.

(1) For image acquisition, monocular cameras have an irreconcilable contradiction in terms of the angle of view and distance, that is, the wider the angle of view, the shorter the distance that can be precisely detected and the less the information that can be obtained. Moreover, monocular vision cannot yield the depth information of the workpiece. However, the application of binocular vision and even multi-eye vision can compensate for this shortcoming. The combination of computer vision positioning technology and multi-sensor technology can provide multi-directional and in-depth information of workpieces and can locate workpieces accurately. This represents one of the development directions for computer vision positioning.

(2) Regarding the lighting scheme, the success of a computer vision positioning system depends primarily on the quality of the lighting device. A suitable lighting scheme will improve the efficiency and accuracy of the vision system. Nonetheless, according to our research, there is no literature regarding specific layouts of the lighting system, and most systems use LED lights (bar, ring, point light source), which offer satisfactory color rendering and longevity but have an unchangeable brightness and intensity. Therefore, a compound light with adjustable intensity and brightness or a combined light (combination of multiple light sources) should be developed. The future vision positioning system should have a stable, and detachable light source device which should have universal applicability and be applicable to multiple fields and multiple scenarios.

(3) For image preprocessing (image enhancement, image segmentation, etc.), The results of image preprocessing directly affect the accuracy of subsequent processing and positioning. In terms of image enhancement, researchers have already developed a relatively complete enhancement scheme for images under normal light and a lot of research on image enhancement under low light, but a relatively complete theory has not been formed. Existing image processing methods ignore the influence of noise on image quality. Recently, researchers have combined convolutional neural networks with existing theories (dehazing models and Retinex theory) with good results. Therefore, the implementation and application of convolutional neural networks (CNN, Deep CNN, GAN, etc.) in weak light enhancement is the future development trend. Additionally, the methods of strong light enhancement are relatively few, and the future research will be an important topic. In terms of image segmentation, traditional segmentation methods are mainly based on the low-level features of the image. Although a rough result can be obtained, the accuracy and speed are not satisfactory. With the development of artificial intelligence and deep learning, the combination of deep neural networks (FCN, SegNet, GAN, U-Net, etc.) and image segmentation will become an inevitable trend. An image segmentation method that could be universally adaptable and be used across domains will be the focus of research.

(4) Positioning algorithm is the core of positioning processing in machining, with the main content of feature extraction and template

matching. Incorporating deep learning on the basis of existing positioning algorithms will result in better positioning results. However, which one can get better results, a separate deep learning algorithm or a combination of it with traditional algorithms? Therefore, deep learning positioning should be further explored. Feature descriptors (HyNet, SOSNet, HardNet, etc.) methods appeared in recent years have been proved to have good feature description capabilities, but these methods are rarely applied to processing and positioning. Whether the methods can be applied to machining still needs researchers to practice and verify.

(5) In terms of machining systems based on visual positioning, automatic positioning systems provide more accurate position information for machining than traditional systems do. This enables high-precision operations (cutting, welding, laser processing, water jet cutting, etc.). However, the shape and position of the workpiece have a great influence on machine vision positioning, so it is possible to establish a large database containing various shapes of the workpiece for the subsequent extraction or matching of features for accurate positioning. Moreover, for the positioning of the workpiece on the assembly line, real-time and online positioning and processing can be realized through the combination of deep learning and visual positioning. The processing of fixed workpieces, on the other hand, can be matched and positioned by comparing with the template of the database. Furthermore, multi-information fusion technology is expected to emerge with the development of visual technology and deep learning. In the future, a cross-domain visual positioning system suitable for most processing objects will become possible.

CRediT authorship contribution statement

Wenbin He: Conceptualization, Writing – original draft, Funding acquisition. **Zhiwen Jiang:** Investigation, Formal analysis, Writing – original draft. **Wuyi Ming:** Creative idea, Supervision, Writing – review & editing. **Guojun Zhang:** Writing – review & editing, Funding acquisition. **Jie Yuan:** Data analysis. **Ling Yin:** Data analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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