A Comprehensive Review of Robotic Sorting Using Machine Vision Technologies

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Abstract

With the rapid development of machine vision technology and artificial intelligence, contemporary robots are evolving towards collaboration, automation, networking, and intelligence. To ensure precise and efficient operation, machine vision technology has garnered significant attention and is being widely applied across various fields. Traditional sorting processes are heavily influenced by object characteristics. However, machine vision technology offers advantages such as high speed, large information capacity, and multifunctionality, while also eliminating errors caused by worker fatigue. Therefore, machine vision technology demonstrates excellent application prospects in the field of sorting.

Based on this, this paper provides a detailed analysis and discussion of the composition, key technologies, and current applications of sorting robots using machine vision technology in various industries. It elaborates on the corresponding advantages, existing problems, and feasible solutions. Finally, the paper explores the development trends of sorting robots integrated with machine vision technology in the era of artificial intelligence and big data.[1.2.4]

Keywords: Sorting robots; Machine vision technology; Artificial intelligence; Object recognition; Image processing

Introduction

Vision and Machine Vision

Vision is the perception generated when retinal stimulation occurs due to the image of an object. Humans perceive the external environment primarily through sensory organs such as vision, touch, hearing, and smell, with approximately 80% of the information acquired through vision.

Machine vision refers to the process where machines automatically process images and report their content. Machine vision technology utilizes light-sensitive components and computer technology to simulate human visual functions. It replaces human eyes in tasks like measuring object similarity and performing pattern recognition based on the features of target images.

With the rapid development of visual sensor technology, computer technology, image processing techniques, and artificial intelligence, machine vision technology has become increasingly mature. It is now a core technology in modern manufacturing and green industries. Its scope includes visual sensor technology, light source illumination, optical imaging, digital image processing, analog and digital video technology, computer hardware and software, and automatic control systems.[2.4.5.7]

Not only can machine vision technology replicate most of the functions of the human eye, but it can also accomplish many tasks that human eyes cannot perform.

The Evolution of Sorting Robots

Traditional sorting work primarily relied on manual labor. However, with the increasing pace of industrial automation, human vision is evidently unable to keep up with the fast-paced and high-intensity demands of modern industrial production. Consequently, many aspects of production have been replaced by robots.

Under the backdrop of a new wave of technological revolutions and industrial transformations, sorting robots have emerged and thrived. Automated sorting technology is gradually becoming mainstream in industrial production. Integrating machine vision technology into sorting robots reduces the workload of manual sorting, lowers sorting error rates, significantly improves production efficiency, and realizes automated and intelligent sorting operations.

Traditional Sorting and the Rise of Sorting Robots

Traditional sorting tasks were primarily completed manually. However, as industrial automation has advanced, human vision has struggled to keep up with the fast-paced, high-intensity demands of modern industrial production. Consequently, many aspects of the production process have been replaced by robots.

Amid the backdrop of a new wave of technological revolution and industrial transformation, sorting robots have rapidly developed. Automated sorting technology has gradually become the mainstream in industrial production. The integration of machine vision technology into sorting robots significantly reduces manual sorting workloads, decreases error rates, greatly enhances industrial production efficiency, and achieves automation and intelligence in sorting operations.

In developed countries, machine vision technology has undergone years of refinement, achieving a high degree of maturity. In contrast, machine vision technology in China started later and lags behind developed nations in terms of advancement.[3.6.7.12.13] However, with the decline in the population dividend and the growing demand for industrial robots in the Chinese market, sorting robot technology has experienced rapid development.

Against this backdrop of applying machine vision technology in sorting, this review focuses on the applications of sorting robots in various fields and provides an outlook on the future trends of related technologies.

Machine Vision Technology

Development of Machine Vision Technology

Machine vision technology is an important branch derived from computer science. Over several decades, it has evolved from its initial stages to its current advanced state, continuously expanding its functions and applications.

- **1950s:** Scholars abroad began leading the research on statistical pattern recognition of 2D images.
- **1960s:** Roberts shifted the focus to 3D machine vision.
- **1970s:** The Massachusetts Institute of Technology (MIT) established the first "Machine Vision" course in its Artificial Intelligence Laboratory. [2.3.5.9.12]
- **1980s:** Machine vision technology saw a global wave of research, with rapid advancements and the introduction of new concepts, technologies, theories, and methods.
- **1990s:** Computer image acquisition devices were gradually upgraded. Image processing technology and robotic control systems continued to develop, making machine vision algorithms a primary focus of research.
- **Late 20th Century:** Zhang introduced a calibration method based on two-dimensional planar targets, which could solve the internal and external camera parameters. In the early 21st century, Lowe's Scale-Invariant Feature Transform (SIFT) method for feature extraction was further developed and widely applied in fields such as machine vision and 3D reconstruction.
- **Early 21st Century:** Lowe's development of the SIFT (Scale-Invariant Feature Transform) feature extraction method was significantly refined and widely applied in fields such as machine vision and 3D reconstruction.

- **2006:** Hinton and others launched the deep learning wave in machine vision research, a core development in the field.
- **2012:** Krizhevsky and his team made a breakthrough in the ImageNet image recognition competition using convolutional neural networks (CNNs). Their network, AlexNet, was the first to employ the Rectified Linear Unit (ReLU) activation function, improving convergence speed and addressing the gradient vanishing issue.
- **2020:** Belan introduced a machine vision system (Machine Vision Studio, MVS) for quality inspection, proving its robustness and feasibility through experimental results.[13.14.17]

With the rapid growth of manufacturing and logistics industries, sorting robots have been widely adopted across various sectors. The key technology behind these robots is machine vision. With its introduction, sorting processes have become more accurate and efficient, and sorting robots have evolved quickly towards more intelligent and automated operations.

Machine Vision Technology in the Era of Artificial Intelligence

Machine vision technology is a crucial component for achieving artificial intelligence and intelligent manufacturing. It plays a vital role in tasks such as defect detection of products in industrial automation environments, machine vision-guided positioning, and more, all of which are key to industrial robots replacing human labor.

Together with artificial intelligence, machine vision technology allows machines to have both eyes and brains. It is one of the core areas of artificial intelligence and an important driving force behind the advancement of AI.

The relationship between machine vision technology, artificial intelligence, and other fields is illustrated in Figure 1.

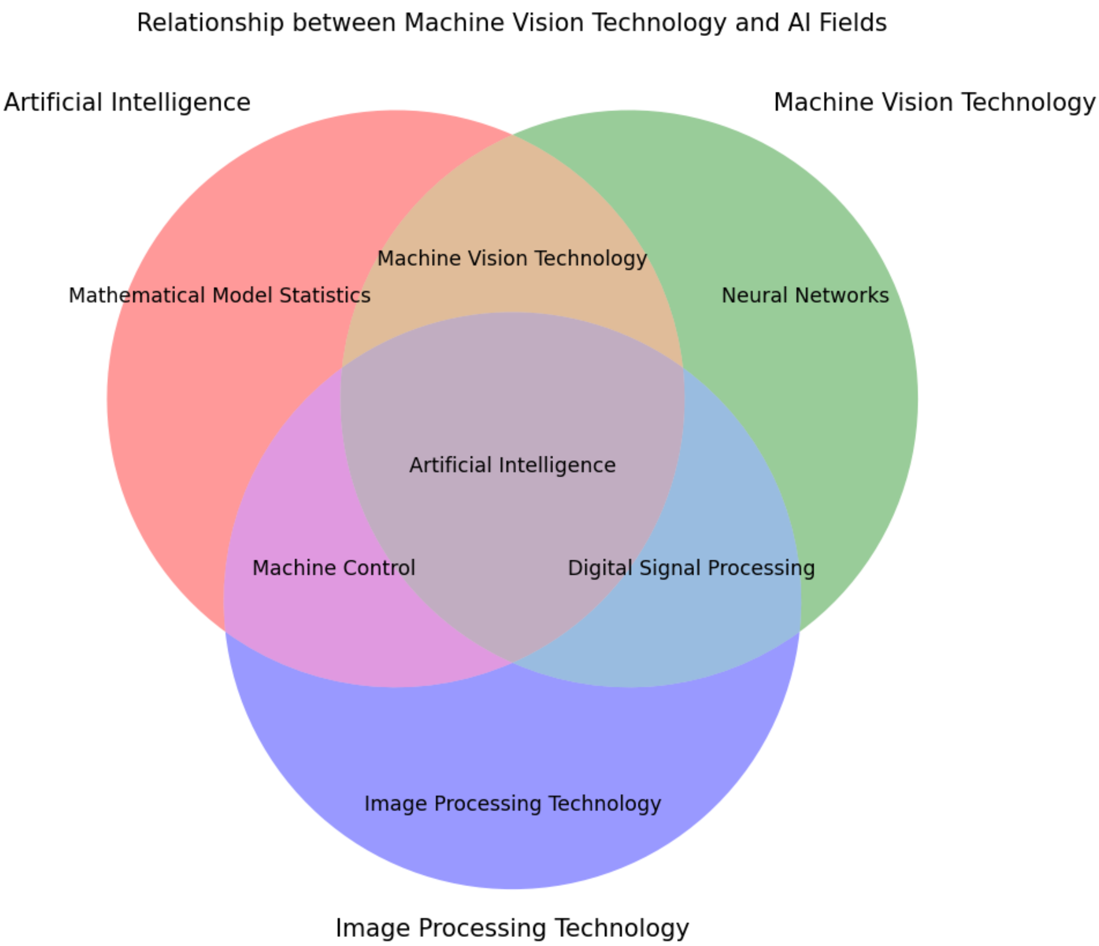

Figure 1 The connection between machine vision technology and other fields.

Machine vision technology is an interdisciplinary field that is closely linked to many other domains. Its relationship with artificial intelligence is particularly strong, having a profound impact on the development of the manufacturing industry, and significantly enhancing production flexibility and automation. With continuous exploration and innovation, a new era of machine vision technology is rapidly approaching. Products based on machine vision technology will soon be applied to various fields, especially in complex and harsh environments.

The main research directions in machine vision technology include multi-sensor information fusion, deep basic vision, visual deep learning, active vision, complete 3D scene reconstruction, visual parallel computing structures, and universal visual information systems.[4.7.20]

In the context of the artificial intelligence era, methods combining machine vision with other sensors will become a research hotspot. However, machine vision research in laboratories is generally conducted under ideal and fixed environmental conditions, with input sources often being still or instantaneous visual information, which makes it difficult to meet the demands of understanding the complex real world. Multi-sensor information fusion refers not only to the fusion of multiple sensors themselves, but also to the fusion of information channels within each sensor system, the integration of system modules, and the merging of various information processing methods. This multi-sensor information fusion will make machine vision technology more accurate and efficient in applications, and will also make artificial intelligence smarter, better equipped to serve humanity.

Image Processing Technology

The work process of sorting robots can be understood as the process in which the robot’s end effector, guided by machine vision, reaches the corresponding position to grasp the object and places it in a designated location, as shown in Figure 2.

First, the vision camera should be calibrated to ensure it can accurately capture the object's image. The next and most critical step is image processing, where the object’s coordinates and features are determined through image processing. This information is then converted into the coordinates and posture of the end effector, ensuring that the sorting task is completed accurately and efficiently.

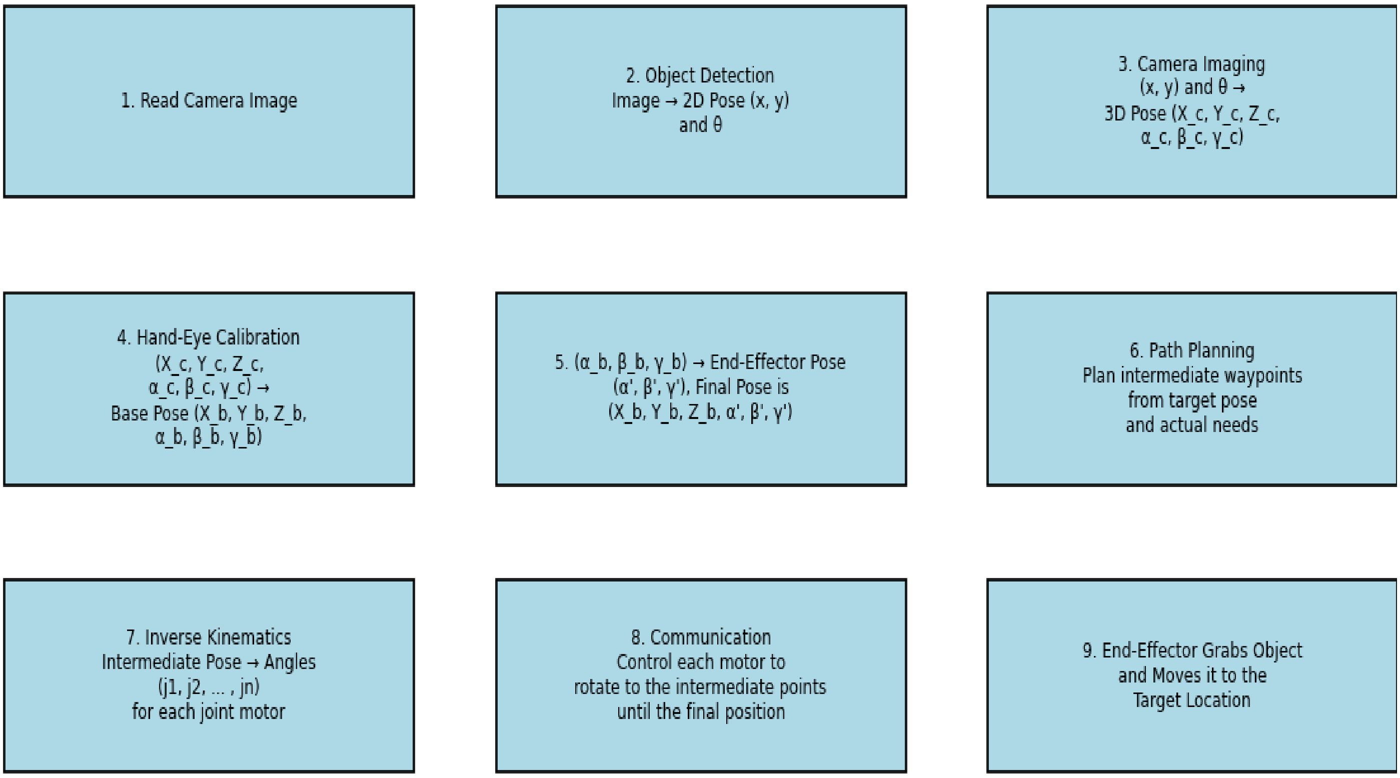

Figure 2 Sorting Robot Workflow Diagram

Image Processing Technology

Image processing technology is a technique that uses computers to process image information, mainly including image preprocessing, image digitization, image enhancement and restoration, image data encoding, image segmentation, morphological processing, image projection, registration and localization, and image feature extraction. Through image processing, the useful information in the image can be enhanced while reducing the data volume. It is a key factor in determining whether the sorting process can be precise and efficient.[10.9.16.22]

Image Preprocessing

Image preprocessing involves classifying each text image and sending it to the recognition module for further processing. Common methods include image filtering, binarization, and edge detection.

Image Filtering

Techniques such as mean filtering, median filtering, Gaussian filtering, BM3D filtering, and bilateral filtering are widely used to eliminate or suppress noise in images.

Image Binarization

Binarization converts the pixel gray values of an image to either 0 or 1, making the entire image exhibit distinct black-and-white effects. This process results in a binary image that reflects both global and local features of the original image. By significantly reducing the amount of data contained in the image, binarization simplifies subsequent processing steps. The most used binarization methods are Otsu's method and the Kittler method. Otsu's method focuses on thresholding principles to optimize segmentation.

Edge Detection

Using edge features to represent the entire image reduces the memory data significantly. Common edge detection methods include Sobel edge detection, Laplacian edge detection, Canny edge detection, and Hough transform line detection.

Image Enhancement

The goal of image enhancement is to highlight valuable information within the image. The final aim is to improve the image's visual effect and readability. Image enhancement can be divided into two main categories: spatial domain methods and frequency domain methods.

$$g(x,y) = T[f(x,y)]$$

In the equation, f (x, y) represents the image before enhancement, g(x, y) represents the image after enhancement, and T denotes the enhancement operation. Spatial domain methods primarily focus on directly calculating and processing the grayscale values of the image's individual pixels in the spatial domain. On the other hand, frequency domain methods process the image's transformation coefficients in a certain transformed domain through specific operations, and then return the processed result to the spatial domain. Thus, frequency domain methods can be considered as an indirect enhancement algorithm.[2.5.11.19]

Image Segmentation

Image segmentation refers to the process of dividing an image into several specific or uniquely characteristic regions and extracting the required objects from them. Commonly used image segmentation methods include threshold segmentation, region-based segmentation, edge-based segmentation, and specific segmentation.

However, today, most image segmentation algorithms are designed for specific problems and lack a universal or standardized approach. Therefore, image segmentation technology is evolving towards being faster, more accurate, and standardized, making it a significant area of research.

Feature Extraction and Recognition

Feature extraction and recognition are familiar concepts. Feature extraction involves obtaining characteristic information from an image, serving as the foundation for image compression, understanding, classification, and recognition.

Image Features

Image features refer to the inherent traits or attributes of an image. These include low-level features such as color, texture, shape, and region structure. The robustness of feature extraction algorithms directly affects the robustness of the entire defect detection system and can even impact the system's stability.

Currently, commonly used image features include:

- Hu Moments Invariant: Known for their robustness in rotation, scaling, and translation.
- Haar-like features: Often used in object detection.

- SURF (Speeded-Up Robust Features): Known for their efficiency and robustness.

Sorting Robots

Sorting robots are a type of robot equipped with sensors, optical lenses, and electro-optical systems, capable of sorting objects with precision and efficiency. Their primary task involves categorizing items based on type or inbound/outbound order and placing them in designated locations.

Vision-Based Sorting

Vision-based sorting delegates the processes of object recognition and classification to the robot's vision system. By leveraging machine vision technology, sorting robots:

- **Increase Sorting Speed**: Automation ensures rapid item processing.
- **Ensure Sorting Quality**: Advanced vision algorithms enhance accuracy.
- **Reduce Labor Intensity**: Automating repetitive tasks alleviates workers' physical strain.
- **Improve Human Efficiency**: Staff can focus on more skilled tasks, increasing overall productivity.

These contributions significantly advance social development and lay a solid foundation for further advancements in artificial intelligence. Sorting robots exemplify the integration of technology into practical applications, transforming industries and streamlining operations.[7.11]

Components of Sorting Robots

Sorting robots are advanced mechatronic devices integrating mechanical, electrical, and computational systems. They consist of three main parts and six subsystems.

Main Parts

1. Mechanical Component
2. Sensor Component
3. Control Component

Subsystems

The six subsystems include:

1. Drive System
2. Mechanical Structure System
3. Perception System
4. Robot-Environment Interaction System
5. Human-Machine Interaction System
6. Control System

1. Drive System

The drive system can be categorized into three types:

- **Hydraulic Drive**: Suitable for handling large objects due to its high-power output.
- **Electrical Drive**: Known for excellent control performance, often used in high-precision sorting robots.
- **Pneumatic Drive**: A flexible and cost-effective system with a low power-to-weight ratio.

2. Mechanical Structure System

This forms the fundamental framework of the sorting robot, comprising:

- **Actuators**: Perform predefined actions.
- **Transmission Mechanisms**: Transfer power, motion, and information.
- **Support Components**: Provide structural stability.

The **end-effector** is the key element in the robot's topology, which can be divided into:

- **Pneumatic Suction Types**: Utilize air pressure for handling objects.

- **Mechanical Gripper Types**: Use gripping mechanisms for object manipulation.

3. Perception System

The perception system integrates internal and external sensor modules to gather valuable information about the robot's environment and operational status. It plays a central role among the subsystems.

- **Machine Vision**: A critical subcomponent of the perception system, enabling the robot to accurately and efficiently sort objects based on their visual properties, transport them, and classify them according to predefined patterns.

4. Robot-Environment Interaction System

This system ensures communication and coordination between the sorting robot and its surrounding environment. It allows the robot and external devices to function as a cohesive unit.

5. Human-Machine Interaction System

This subsystem serves as a bridge between operators and the robot. It facilitates:

- **Control**: Allows human oversight and intervention.
- **Communication**: Ensures smooth information exchange.
- **Information Management**: Enhances functionality in data processing, management, and services.

By integrating this system, computers and artificial intelligence evolve into a practical technology for human learning and work.[3.11.12.20]

6. Control System

The control system is the core component of sorting robots, directly influencing their performance. It plays a vital role in:

- **Internal Coordination**: Ensures smooth operations within the robot.
- **Collaborative Operations**: Coordinates multiple sorting robots working together.

This subsystem drives the advancement of sorting robot technologies and their application in various industries.

Machine Vision Technology in Sorting Robots

Machine vision technology involves capturing, processing, and analyzing images and videos from the real world. Integrating this technology into sorting robots enables them to extract meaningful contextual information from the physical environment. This includes applications such as:

- Machine Vision Recognition
- Optical Character Recognition (OCR)
- Image Recognition
- Pattern Recognition
- Facial Recognition
- Edge Detection
- Motion Detection

For different objects, the most prominent feature is often their **shape**. As a result, shape recognition technology based on machine vision plays a vital role in sorting processes. This technology enhances sorting precision and efficiency, saving space while speeding up outbound processes. Applying machine vision to the sorting robot industry propels it toward **automated** and **intelligent sorting systems**.

Key Technologies in the Sorting Process

Camera Calibration Technology

Camera calibration is a critical technique for reducing image data errors during acquisition. Unlike the human eye, cameras convert received light signals into digital signals and then quantify them into a numerical matrix.[17.18.19.22]

Image Data Formats

Camera-generated data formats vary widely but are generally classified into:

- **2D Image Data**
- **3D Point Cloud Data**

High precision is required for optical devices like cameras. Various internal and external factors during image acquisition can cause distortions in object images. To mitigate such errors, camera parameters must be calibrated before image collection.

Traditional and Modern Calibration Methods

1. **Traditional Calibration**

- Requires capturing a **3D calibration target**.

2. **Modern Calibration**

   - Uses **2D planar targets**, such as those supported by MATLAB calibration tools or Zhang Zhengyou's calibration method.

Chessboard Pattern Calibration Target

The study showcases a chessboard calibration target. Parameters such as size, square, image, and camera are modified based on the camera and chessboard dimensions.[11.13.17.19.20.22]

Improving Calibration Accuracy

To ensure accurate calibration:

- The target should appear in all areas of the camera's field of view.
- Move the target **up, down, left, right, forward, backward, rotate, and tilt** continuously until the parameter collection process is complete.

Once the progress bar in the interface indicates completion, click "Finish".

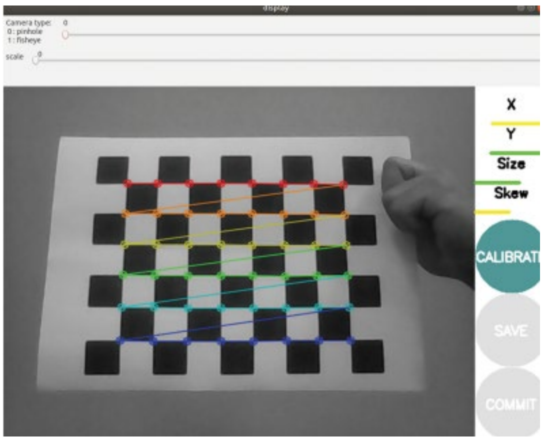

Figure 3 Camera Calibration Procedure

Conclusion and Outlook

Machine vision technology is a crucial component in the field of sorting robots, expanding their research directions and application domains. Sorting robots based on machine vision technology have been widely applied in industries such as food, coal, logistics, electronics manufacturing, and automotive production. The development of machine vision technology benefits from advancements in computer and camera performance, as well as the optimization and innovation of core algorithms. It has made sorting robots more efficient, intelligent, and user-friendly. This article introduces the composition and key technologies of sorting robots from the perspective of machine vision, analyzes potential research directions, and reviews the current applications of machine vision-based sorting robots in various fields.

Despite their widespread use in many industries, sorting robots based on machine vision technology still face challenges and limitations during implementation:

1. **Complexity of Sorting Objects**
Due to the variability in shape and material of sorting objects, machine vision systems must process large volumes of complex information. Current algorithms are time-consuming, making it difficult to achieve precise and efficient sorting. Developing new machine vision algorithms with enhanced feature extraction, selection, and classification capabilities is urgently needed to make efficient and accurate sorting a reality.

2. **Embedded Machine Vision Systems**
Embedded machine vision systems integrate advanced computing, semiconductor, and electronic technologies, enabling real-time image acquisition and processing without requiring high-end computers. These systems make sorting robots more compact, reduce costs, and lower power consumption. Integrating embedded machine vision into sorting robots is a key future research direction.

3. **Environmental Adaptability and Multi-Sensor Fusion**
Unlike humans, sorting robots lack keen vision, and their algorithms are significantly affected by environmental factors. Single-source machine vision is insufficient for complex sorting scenarios. Equipping robots with multiple types of sensors and enabling automated analysis and integration of multi-source data can enhance their adaptability for object recognition, precise positioning, and flexible manipulation. However, there is no unified fusion

theory or effective generalized fusion models yet. Future efforts should focus on developing standardized fusion theories, architecture, and algorithms, incorporating AI and big data to improve performance, and establishing data fusion evaluation platforms and management systems.

4. **Artificial Intelligence and Machine Vision Integration**

While machine vision is almost standard in sorting applications, traditional algorithms still dominate, with limited use of AI-driven machine vision. Combining AI with machine vision enhances sorting flexibility, allowing systems to adapt to various positions, lighting, and environments. However, the accuracy of AI algorithms remains a bottleneck, with most systems achieving only around 85% accuracy. Improving accuracy is a critical and challenging future research focus.

5. **Integration of 5G and Deep Learning**

The advent of 5G, with its high speed, low latency, and large connectivity, complements deep learning algorithms. This integration enhances machine vision systems by combining efficiency and robustness with human-like adaptability. Machine vision sorting systems leveraging 5G and deep learning can handle high-resolution images and support multi-robot collaboration, accelerating the development of smart sorting factories and paving the way for future "super factories."

The continued evolution of machine vision technology promises transformative advances in sorting robots, driving automation, intelligence, and efficiency across industries.

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