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Research and Application of Coordinate Calibration Methods for Machine Vision-Based Robots

Quang Minh Duong*
Faculty of Mechanical Engineering, Thai Nguyen University of Technology, Vietnam
**Corresponding Author*

ABSTRACT: *Robot-integrated machine vision systems have become an essential component of modern automated manufacturing lines. However, the operational accuracy of robotic systems strongly depends on the calibration accuracy between cameras, sensors, and robot coordinate systems. This paper presents an overview of coordinate calibration methods for robot-integrated vision systems, including camera calibration, hand–eye calibration, and robot kinematic calibration. The study focuses on analyzing commonly used calibration algorithms such as Zhang's method, homogeneous transformation matrices, and nonlinear optimization techniques. In addition, the applicability of laser sensors in industrial robot vision systems is also evaluated. The research results indicate that the integration of calibration algorithms with image processing techniques and laser sensors significantly improves positioning accuracy, reduces calibration errors, and enhances the overall performance of robotic systems in smart manufacturing environments.*
Keywords: *Machine vision, industrial robots, coordinate calibration, laser sensors, camera calibration, hand–eye calibration.*

NOMENCLATURE

Symbol	Description	Unit
K	Intrinsic camera matrix	–
R	Rotation matrix	–
t	Translation vector	mm
M	3D point in world coordinates	mm
m	Image point coordinate	pixel
s	Scale factor	–
A	Robot motion transformation matrix	–
B	Camera motion transformation matrix	–
X	Hand–eye transformation matrix	–

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I. INTRODUCTION

In recent years, the rapid development of automation technologies and artificial intelligence has significantly accelerated the application of industrial robots in various manufacturing sectors. Modern robotic systems are not only capable of performing repetitive tasks but can also perceive their surrounding environment and interact flexibly with objects through machine vision technology. Robot vision systems enable robots to acquire image data, analyze object positions and geometries, and consequently support high-precision manipulation and control operations.

According to recent studies, the integration of machine vision with robotic systems considerably improves production efficiency, reduces operational errors, and enhances automation capabilities in applications such as quality inspection, automated welding, assembly, and robot guidance [1], [2]. In addition to conventional 2D vision systems, 3D vision technologies based on stereo vision and laser sensors are increasingly being adopted due to their capability to provide depth information and accurate spatial modeling [3], [4]. However, for robots to perform precise operations based on data acquired from cameras or sensors, coordinate calibration is an indispensable requirement.

Coordinate calibration aims to determine the geometric relationships among different coordinate systems, including the camera coordinate system, robot coordinate system, and object coordinate system. Inaccurate calibration may lead to positioning deviations during robotic operations, thereby reducing product quality and operational efficiency. Various calibration methods have been studied and implemented in practice. Among them, Zhang's camera calibration method is considered one of the most widely used algorithms because of its capability to accurately estimate both intrinsic and extrinsic camera parameters [5]. Furthermore, nonlinear optimization algorithms and machine learning-based approaches have also been developed to improve calibration accuracy in complex environments [6], [7].

This paper focuses on the study of coordinate calibration methods for robot-integrated vision systems while also analyzing the applicability of laser sensors in modern industrial robotic systems.

II. OVERVIEW OF ROBOT-INTEGRATED VISION SYSTEMS

A robot vision system is a combination of cameras, sensors, image processing units, and industrial robots designed to enable robots to perceive and understand their surrounding environment. Image data acquired from cameras are processed to determine the position, size, and shape of objects, thereby supporting robots in performing accurate operations.

Current robot vision systems can generally be classified into three main categories:

- 2D vision systems.
- 2.5D vision systems.
- 3D vision systems.

2D vision systems offer advantages such as low implementation cost, simple deployment, and high processing speed. However, their major limitation is the inability to provide depth information of objects. In contrast, 3D vision systems employing stereo vision or laser sensors are capable of reconstructing spatial models, allowing accurate determination of object positions in three-dimensional environments.

In robot vision systems, cameras and robots typically operate in different coordinate frames. Therefore, image data obtained from the camera must be transformed into the robot coordinate system to enable accurate robotic manipulation. This process is achieved through coordinate calibration.

Coordinate calibration provides several important benefits, including:

- Accurate determination of the camera position and orientation.
- Coordinate synchronization between the camera and the robot.
- Reduction of positioning errors.
- Improvement of robotic manipulation accuracy.
- Enhancement of system stability and repeatability.

In industrial applications requiring high precision, such as automated welding, electronic assembly, and quality inspection, even small calibration errors can significantly affect product quality and overall system performance.

III. COORDINATE CALIBRATION METHODS

A. Camera Calibration

Camera calibration is the first step in robot vision systems for determining the intrinsic and extrinsic parameters of the camera (Fig 1). The intrinsic parameters include:

- Camera focal length.
- Principal point.
- Lens distortion coefficients.

The extrinsic parameters describe the position and orientation of the camera in real-world space. One of the most widely used approaches is Zhang's calibration algorithm. This method utilizes multiple images of a calibration checkerboard captured from different viewpoints to estimate the camera parameters. The main advantages of Zhang's method are its ease of implementation, no requirement for specialized equipment, and high calibration accuracy.

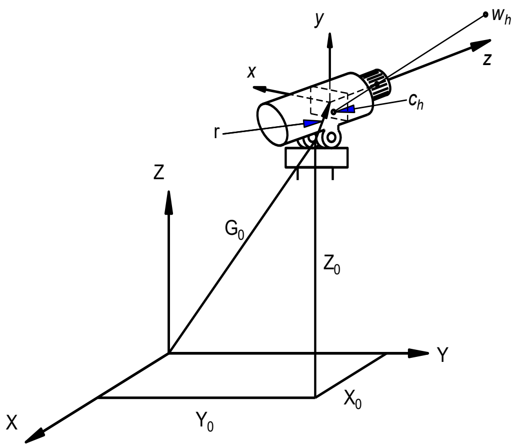

Fig. 1. Geometric Model of the Camera

The mathematical model of a camera is commonly represented by the following equation:

$$sm = K[R\,|t]M \quad (1)$$

where:

- M is the coordinate of a point in real-world space.
- m is the image point coordinate.
- K is the intrinsic camera matrix.
- R and t represent the rotation matrix and translation vector, respectively.
- s is the scale factor.

After calibration, geometric distortion errors of the camera can be compensated for, thereby improving the accuracy of the vision system.

B. Hand–Eye Calibration

Hand–eye calibration is used to determine the relationship between the camera coordinate system and the robot coordinate system. This is a critical step in vision-guided robotic systems.

The hand–eye calibration problem is commonly formulated as:

$$AX = XB \quad (2)$$

where:

- A is the robot motion transformation matrix.
- B is the camera motion transformation matrix.
- X is the transformation matrix between the camera and the robot that needs to be determined.

Two common configurations are widely used:

- Eye-in-hand: the camera is mounted directly on the robot end-effector.
- Eye-to-hand: the camera is fixed externally in the workspace.

The eye-in-hand configuration provides high flexibility and is suitable for applications requiring close observation of objects. In contrast, the eye-to-hand configuration is more appropriate for large workspaces and applications requiring global monitoring.

C. Robot Kinematic Calibration

Robot kinematic calibration aims to improve the positioning accuracy of robots by correcting kinematic parameters such as link lengths, joint angles, and assembly errors.

In practice, industrial robots often exhibit positioning errors caused by:

- Mechanical manufacturing inaccuracies.
- Joint backlash.
- Thermal deformation.
- Sensor errors.

Kinematic calibration helps reduce positioning errors and improve robot repeatability without requiring modifications to the mechanical structure of the robot.

IV. APPLICATION OF LASER SENSORS IN ROBOT VISION SYSTEMS

Line laser sensors operate based on the principle of optical triangulation. A laser beam is projected onto the surface of an object, while a camera captures the reflected laser line image. By analyzing the positional variation of the laser line in the captured image, the system can calculate the height or surface geometry of the object.

Compared with conventional 2D cameras, laser sensors offer several advantages, including:

- Accurate acquisition of 3D data.
- Reduced sensitivity to ambient lighting conditions.
- High measurement resolution.
- Fast measurement capability.

Laser sensors have been widely applied in various industrial applications, such as:

- Product quality inspection.
- Automated welding.
- Robot guidance.
- Dimensional and shape measurement.
- Reverse engineering.

Many commercial systems, such as AutoGuide, iRVision, and Servo Robot, have integrated laser sensors to enhance manipulation accuracy and object recognition capabilities in manufacturing environments. In modern production lines, laser sensors enable robots to detect positional deviations in real time and automatically adjust their motion trajectories accordingly.

V. EVALUATION AND DISCUSSION

The research results are presented in Figure 2, Table 1, and Table 2. The obtained results demonstrate that coordinate calibration plays a critical role in the accuracy of robot vision systems. The integration of camera calibration, hand–eye calibration, and robot kinematic calibration significantly reduces robot positioning errors.

In systems utilizing 2D cameras, errors commonly arise from image distortion and the lack of depth information. In contrast, systems employing laser sensors or stereo vision provide higher accuracy but require greater investment costs and more complex processing algorithms.

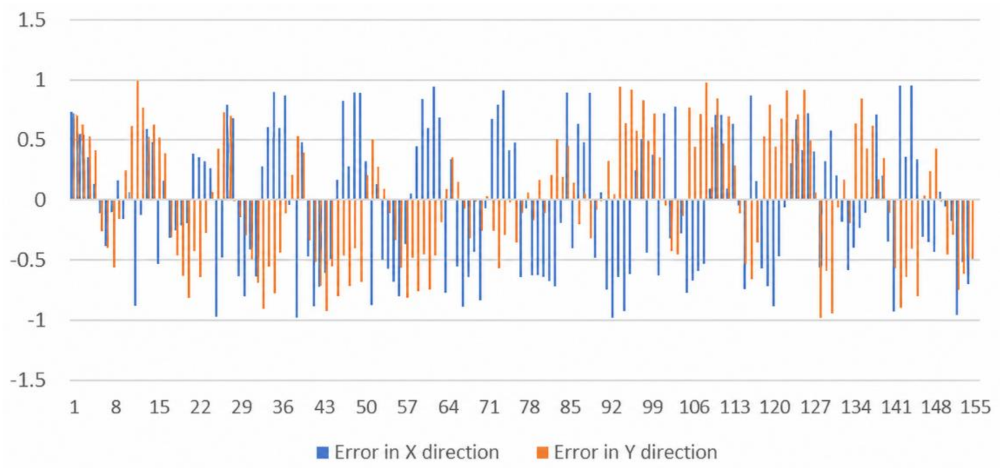

Fig. 2. Calibration Errors Along the OX and OY Directions

Table 1. Image Coordinates of Real Objects in the Workspace

No.	Object	x (pixel)	y (pixel)
1	1	1143	493
2	2	924	491
3	3	718	529
4	1	1241	505
5	2	988	418
6	3	385	264
7	3	656	295

Table 2. Actual Coordinates of Objects in the Workspace

No.	Object	X (mm)	Y (mm)
1	1	490.6879	248.2979
2	2	361.5958	248.9499
3	3	240.3345	273.1283
4	1	548.6749	254.5737
5	2	398.5677	205.5477
6	3	45.8748	121.5358
7	3	203.6572	136.9341

In addition, the application of nonlinear optimization algorithms further improves calibration performance, particularly in environments with significant noise or varying lighting conditions. Artificial intelligence and deep learning-based approaches are also being actively investigated to automate the calibration process and enhance system adaptability.

However, the implementation of robot vision systems in practical industrial environments still faces several challenges, including:

- High equipment costs.
- Requirements for powerful computational hardware.
- Algorithmic complexity.
- Errors caused by vibration and industrial environments.
- Difficulties in real-time data synchronization.

Therefore, future research trends are expected to focus on the development of automatic calibration algorithms, accelerated data processing techniques, and enhanced integration between robots and intelligent sensing systems.

VI. CONCLUSION

This paper has presented an overview of coordinate calibration methods for robot–integrated vision systems. Camera calibration, hand–eye calibration, and robot kinematic calibration play essential roles in ensuring the operational accuracy of industrial robots.

The study indicates that the use of laser sensors and modern image processing algorithms significantly improves object recognition and positioning capabilities in three-dimensional environments. Furthermore, the integration of machine vision, artificial intelligence, and industrial robotics is opening up new development opportunities for intelligent manufacturing systems.

In the future, further research should focus on optimizing calibration algorithms, reducing implementation costs, and enhancing real–time processing capabilities in order to satisfy the increasingly demanding requirements of modern industry.

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REFERENCES

[1]. Ziliang Miao, Buwei He, Wenya Xie, Wenquan Zhao, Xiao Hu, "LiDAR-based robot vision systems", IEEE Robotics and Automation Letters, 2023.

[2]. Qingdong Wu, Jijun Miao, Zhaohui Liu, Jiaxiu Chang, "Coordinate calibration method for industrial robot systems", Sensors, 2024.

[3]. Lei Wu, Xizhe Zang, Guanwen Ding, Chao Wang, "Joint calibration methods for robot measurement systems", ResearchGate, 2023.

[4]. Xiangsheng Zhang, Meng Yao, Qi Cheng, Gunan Liang, Feng Li, "Vision calibration based on TOF camera", Frontiers in Plant Science, 2022.

[5]. Rui Wang, Anwen Wu, Xuan Chen, Jun Wang, "Machine vision calibration method through image processing", Measurement, 2020.

[6]. Ruixuan Li, Yuyu Cai, Kenan Niu, Emmanuel Vander Poorten, "Robot vision calibration using optimization algorithms", IEEE Robotics and Automation Letters, 2021.

[7]. Safouane El Ghazouali, Alain Vissiere, Louis-Ferdinand Louradour, "Machine learning based calibration methods", Journal of King Saud University – Computer and Information Sciences, 2022.

[8]. Ngoc Vu Ngo, Duong Van Cuong, "Development of an intelligent visual system for a robotic arm using machine vision", IJMERR, 2024.