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Design of Mobile Robot Vision Positioning System

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Abstract

Against the backdrop of rapid advancements in intelligent manufacturing and robotics, enhancing the high-precision autonomous positioning capability of industrial robots in dynamic and complex environments has become a critical challenge. To address the pain points of large initial positioning errors and insufficient accuracy in traditional methods, this study designs and implements a high-precision, high-robustness mobile robot visual positioning system. The system adopts an Eye-in-Hand visual architecture, integrating HOG feature extraction with KCF kernel correlation filtering algorithms to achieve robust target tracking. By combining Blob region analysis with least squares circle fitting, it enables stable recognition and coarse positioning of circular targets, while utilizing binocular vision ranging technology for precise positioning. To improve system accuracy, an error modeling-based pose compensation method is proposed. Experimental results demonstrate that the proposed system effectively enhances the robot's positioning accuracy and attitude control performance, validating its effectiveness and robustness in engineering applications.

Keywords

Machine Vision, Industrial Robot, Error Compensation, Target Tracking, Binocular Ranging.

1. Introduction

As manufacturing transitions toward intelligent and flexible production, industrial robots have become the core equipment of modern production systems. Their autonomous decision-making and precision operation capabilities directly determine production efficiency and product quality. Machine vision technology, particularly visual positioning, serves as a key enabling technology for enabling robots to perceive their environment, identify targets, and perform high-precision operations. However, in practical applications, industrial robots often exhibit significant initial positioning errors due to factors such as model inaccuracies, joint clearance, and load variations, severely limiting their use in high-precision scenarios like precision assembly and automated welding. Therefore, developing a visual system capable of compensating for initial errors and achieving high-precision autonomous positioning holds significant theoretical and engineering value [1].

Visual measurement and control technology has become a core research direction in robotic intelligence. Visual systems can acquire rich environmental information non-contact, achieve target recognition and pose estimation, and provide real-time feedback for path planning and motion control. Scholars worldwide have conducted extensive research in this field, including CAD-model-based visual assembly systems [2], binocular vision navigation systems for specific scenarios [3], and trajectory tracking methods based on the eye-to-hand configuration [4]. These studies have laid a solid foundation for visual servoing and control. However, when facing complex operating conditions such as large initial positioning errors and dynamic scene changes, the system's accuracy, robustness, and real-time performance still require further improvement. This study aims to address these challenges by designing a positioning system that integrates advanced visual algorithms with intelligent control strategies.

2. Construction of Autonomous Positioning System based on Target Features

The system consists of multiple core modules, including a visual measurement system, industrial robot body, end-effector, mobile working platform, target structure, and corresponding control and interaction software. The overall hardware configuration is shown in Figure 1. The KUKA industrial robot and its control cabinet execute high-precision movements, while the binocular vision measurement system captures and processes target images in real time. The mobile platform extends the robot's workspace. All modules are interconnected via a high-speed communication network to ensure real-time and reliable data exchange.

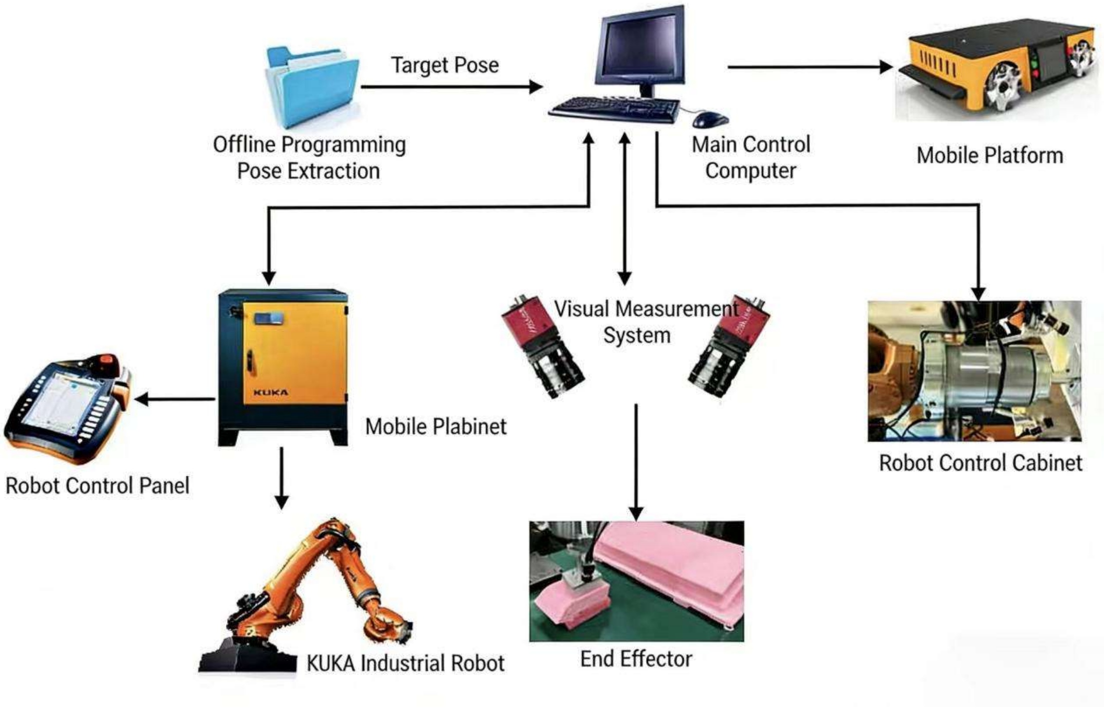

Figure 1. Hardware architecture of machine vision positioning system

3. Design of Binocular Vision Precision Positioning based on Target Characteristics

3.1. Principle of Binocular Vision Measurement

Binocular vision achieves three-dimensional spatial localization through the principle of disparity. To accurately detect circular targets serving as positioning references, this study proposes an identification algorithm that integrates blob analysis with least squares fitting. The process begins with image preprocessing, where blob analysis extracts potential target-connected regions and calculates their centroids as initial positioning points. The centroid calculation formula is as follows:

$$(x_c, y_c) = \left(\frac{1}{N}\sum_{i=1}^{N} x_i, \frac{1}{N}\sum_{i=1}^{N} y_i\right) \tag{1}$$

Then, the edge points of the extracted region are used to fit a circle by least squares, and the coordinates of the center and the radius of the circle are obtained.

3.2. Binocular Vision-based Precise Positioning Control

To achieve continuous tracking of moving or transiently occluded targets, the system employs the HOG-KCF tracking algorithm. This algorithm constructs a robust feature representation by calculating the Histogram of Gradients (HOG) of images, with the gradient magnitude and direction computed as follows:

$$\theta(x, y) = \arctan\left(\frac{G_y(x,y)}{G_x(x,y)}\right) M(x, y) = \sqrt{G_x^2(x, y) + G_y^2(x, y)} \tag{2}$$

Subsequently, a kernel correlation filter (KCF) is employed for efficient learning and detection in the Fourier domain, with the objective function being

$$\min(\|K\alpha - y\|^2 + \lambda\|\alpha\|^2) \tag{3}$$

The tracking algorithm combined with the target recognition algorithm constitutes a visual perception process from coarse to fine.

4. Visual Servo Control and Error Compensation Strategy

4.1. Coordinate Transformation and Hand-eye Calibration

The image coordinates obtained through visual measurement must be transformed into the robot's base coordinate system for controlpurposes. This process involves camera intrinsic parameter (u, v) (X, Y, Z)calibration, binocular extrinsic parameter calibration, and hand-eye calibration. After obtaining the camera intrinsic matrix K, rotation matrix R, and translation vector t through calibration, the relationship between image points and spatial points is defined as

$$s\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = K[R \quad t]\begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} \tag{4}$$

This method lays a foundation for the subsequent precise pose calculation.

4.2. Hybrid Control Strategy and Error Compensation Model

To mitigate initial positioning errors and enhance the system's dynamic performance, this study proposes a hybrid control strategy integrating closed-loop and open-loop $P_{ref}P_{real}$ approaches. The system's core component is a pose error feedback compensation mechanism. Let the theoretical target pose of the robot's end-effector be, and the actual pose measured by the vision system be, then the pose error is

$$\Delta P = P_{real} - P_{ref} \tag{5}$$

Based on this error, the system employs iterative learning for compensation. After each movement, the visual system re-measures the pose and calculates new errors, generating compensation commands to drive the robot toward error reduction. To further enhance convergence speed and $\widehat{\Delta P}$accuracy, a feedforward compensation model is introduced. This model predicts potential error trends from historical error data and incorporates the predicted values into control commands in advance, i.e.

$$P_{cmd} = P_{ref} - \widehat{\Delta P} \tag{6}$$

The feedforward prediction-feedback correction mode can effectively improve the control accuracy and response speed of the system.

5. Experimental Research and Result Analysis

5.1. Visual Tracking and Positioning Experiment

The experimental platform and software system for the KCF-based target tracking system, as shown in Figure 2, were developed. First, the robustness of the target tracking algorithm was tested, demonstrating stable tracking performance even under slight variations in ambient lighting and slow target movement. Subsequently, the core positioning accuracy of the system was evaluated.

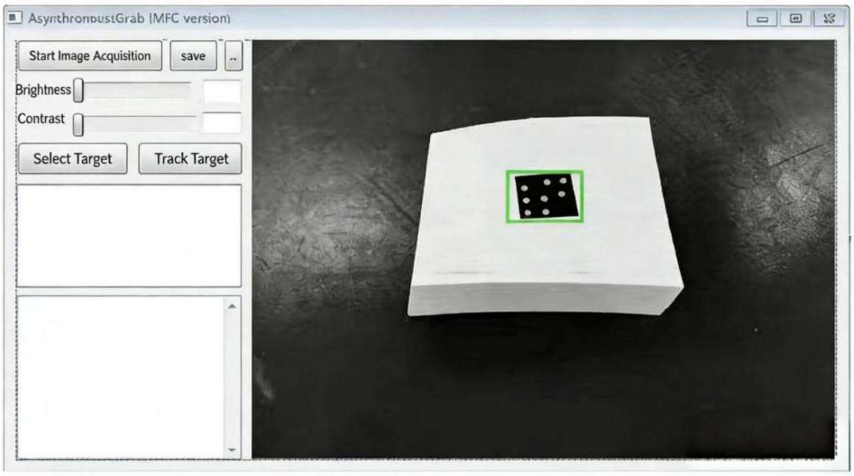

Figure 2. Software interface of target tracking system

5.2. Binocular Vision Precision Positioning Experiment

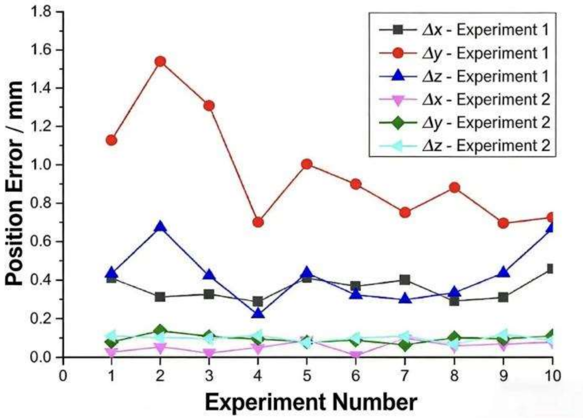

Figure 3. Positioning error of direct positioning and iterative compensation for the robot

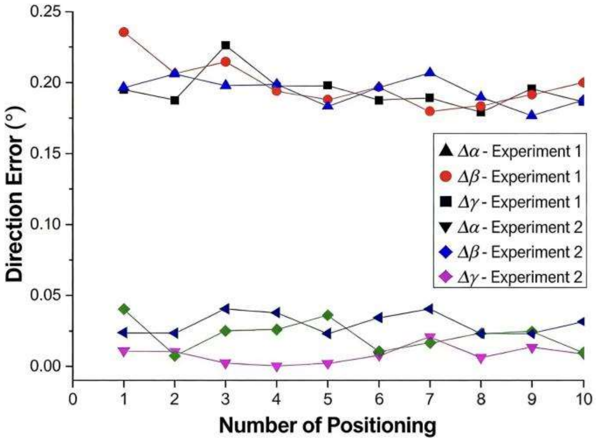

Figure 4. Directional error of direct positioning and iterative compensation for the robot

The experiment compared the positioning performance of the robot under two modes: direct positioning without compensation (Experiment 1) and iterative compensation (Experiment 2). As shown in Figure 3, the positional error remained below 0.15mm in all three axes (X, Y, Z) with compensation, significantly outperforming direct positioning. Figure 4 demonstrates that with iterative compensation, the directional errors (Δα, Δβ, Δγ) were effectively controlled within 0.05°, achieving a substantial improvement in precision.

6. Conclusion

To address the high-precision autonomous positioning requirements of industrial robots, this study developed a machine vision-based positioning system. By integrating Blob analysis, least squares fitting, HOG-KCF tracking, and binocular vision technologies, we constructed a robust visual perception module. An innovative hybrid control strategy combining feedforward and feedback mechanisms, along with an iterative error compensation model, was proposed to effectively resolve the issue of large initial positioning errors. Experimental results demonstrate that the system significantly improves the robot's absolute positioning accuracy and attitude control performance, demonstrating high engineering application value.

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