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Electrical Control System of Harvesting Robotic Arm Based on PLC and Particle Swarm Algorithm

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ABSTRACT

This paper aims to explore a new control system optimization algorithm that combines PLC controller with computer image processing technology to enhance the control performance of a harvesting robotic arm. The algorithm autonomously selects the optimal picking sequence based on the collected images of fruits, significantly reducing the end-effector's operation time and greatly improving work efficiency. By applying the particle swarm algorithm, we compared the distance of the robot's moving tail and the picking accuracy in an actual scenario of harvesting bell peppers. It was found that the application of the particle swarm algorithm can greatly improve the positioning and recognition accuracy of fruit trees and substantially reduce transportation distances, thereby significantly enhancing work efficiency.

Keywords: Harvesting Robotic Arm, Electrical Control System, Particle Swarm Algorithm, PLC Controller, Positioning and Recognition

1. Introduction

Due to the continuous growth of the global population, the challenge we face is how to meet the increasing demand for food supply. Therefore, modern agriculture is moving towards a more efficient and sustainable direction by introducing cutting-edge technologies such as crop protection, seed detection, moisture management, environmental monitoring, and integrating them with intelligent controls from modern engineers. By introducing "smart robots," automated robots can have visual, auditory, olfactory, or other cognitive functions similar to humans, allowing them to better perceive the surrounding environment and respond rapidly to changes [1]. The proliferation of such technology in the industrial field not only brings significant economic gains but also has positive impacts on society [2]. With the development of science and technology, agriculture and biotechnology industries are facing unprecedented challenges, including entities that are vulnerable, adaptable, prone to damage, in need of proper control, diverse, and recognized as life, requiring artificial intelligence to possess characteristics beyond traditional intelligence. With technological advancements, the application of robotic arms is becoming more widespread. They can adapt to extreme weather conditions such as high temperature, corrosion, and toxicity, and they have excellent manipulative accuracy. Their manipulation behavior is not only limited to sensors but also supported by PLC technology, making their operation more straightforward and efficient. Using robotic arms for harvesting operations can significantly reduce human labor intensity and complete the entire operation process within 20 hours. The application of this technology brings enormous benefits to modern agriculture, especially in areas with labor shortages [3].

2. Related Work

"Robotic arm" is a complex mechanical structure that completes specific tasks through connected joints and linkages. Its appearance resembles a human hand, but its working principle is different. It can move an object from one fixed location to another, making it easier for objects to approach each other. It not only assists in tasks but also provides a stable support for objects. With the advent of the 1980s, industrial robotic arm technology advanced significantly, with Stanford/ JPL three-finger hand I and Utah/MIT four-finger hand [4] as benchmarks. The applications of these technologies have become more widespread, especially the Stanford/JPL three-finger hand, which introduced a modular design for fingers with 9 adjustable degrees of freedom [5]. The excellence of the Stanford/JPL hand goes beyond a single mechanical arm; its unique modular structure allows it to have multiple joints and degrees of freedom, combining position, touch, force, and other related information for accurate perception of the surrounding environment, bringing revolutionary changes to human intelligence. Since the late 1980s, many academic institutions have been dedicated to exploring the invention of multi-functional massage devices, with Beijing University of Aeronautics and Astronautics (BUAA) and Harbin Institute of Technology (HIT) being particularly outstanding. BUAA developed the first three-finger massage device and later BUAA-II, BUAA-III Orchid Finger massage devices, while HIT stands out with its inventions that offer users worldwide more convenient options for massage devices and more comfortable massage experiences. Zhang S et al. developed the HIT/DLR multi-finger hand [6]. The 5DOF tomato harvesting robotic arm is considered a pioneer of agricultural robots. It has a unique structure with a spatial open-chain mechanism, which provides high flexibility in capturing and harvesting various types of crops, especially those that require highly precise control. With the increase in the number of links, the size of the robot also becomes larger, especially when handling the picking, sorting, and transportation of crops such as watermelons and cantaloupes, which are more cumbersome than humans. The robot's design needs to consider its load capacity. Developed countries like Japan and the United States have a relatively large number of farmers. However, due to the development of agriculture towards large-scale, diversified, and precise direction, the shortage of labor has become increasingly prominent [7]. Many types of tasks, such as harvesting and transportation of vegetables and fruits, as well as grafting of vegetables, require a considerable amount of technology and skilled expertise. These tasks are often very challenging due to their specificity. Given the current situation, many developing countries actively invest in the development of agricultural robots. Their efforts have yielded significant returns. To achieve this, they not only need to inherit and improve existing robotic arms but also optimize them to enhance their self-regulation capabilities. With the advancement of technology, a new type of four-finger robot has been developed with excellent self-regulation capabilities. It can adjust the gripping force according to different environments, making it easier to complete picking tasks. In addition, through simulation and numerical simulation, we have conducted in-depth research on the elastic deformation of fruit trees and related control algorithms to ensure the theoretical reliability. Japanese agricultural machinery is equipped with advanced sensing technology, enabling accurate control of plant growth and rapid insertion and transplantation. For example, the insertion machine for planting can quickly insert plants several millimeters long, and their insertion speed is very fast. In addition, these devices are equipped with four moderately wide cylinders with a broad range of transportation. By introducing human-robot collaboration robots, robots can autonomously search, locate, and guide and efficiently complete various tasks through their own control systems, such as motion trajectory design, joint manipulation, and end effector operations. Collaboration between research institutions has led to the development of robots with advanced servo vision systems, significantly increasing the efficiency of rural production [8]. Additionally, the "MAGAU" robot from the PeDene and Motte research institutes and the "CITRUS" robot from the Jasa research institute provide more efficient mechanical means for agricultural products, enabling more accurate completion of tasks related to agricultural products [9]. The collaboration between the National Vegetable and Tea Research Institute and Gifu University has produced a new eggplant, cabbage, and melon harvesting robot. The ZhuX research group further studied this and successfully developed a new melon harvesting machine [10]. After capturing the items, the termination device must be able to release them naturally from the captured items. This release is usually done through cutting and pulling. However, when the environment permits, pulling is preferable to avoid damaging the appearance and texture of the captured items and prevent bacteria from growing. For example, for peaches, plums, and apricots, the captured items must be kept intact. However, due to the special structure of some fruits, using traditional cutting techniques to cut them can be challenging, especially if their stems are relatively thin. Therefore, one of the challenges for farmers is how to correctly use harvesting robotic arms to ensure the quality of the harvest. Currently, both domestic and foreign harvesting machine technologies face many challenges, and particular attention is paid to how to improve their efficiency.

3. Mechanical Arm Electrical Control System Technology

3.1. PLC-Based Mechanical Arm Electrical Control System

The advent of PLC systems has made them an ideal industrial device, with features such as high counting ability, compact size, and easy operation, making them the preferred choice in many industrial production and research settings [11,12]. Additionally, the improvement in communication capabilities has further enhanced the performance of PLC systems. A PLC control system typically consists of four important components: CPU, registers, power supply, and input/output interfaces. The CPU is responsible for executing complex tasks; it can acquire data from the external environment and convert it into effective commands, enabling efficient collaboration among various components. The CPU possesses a powerful self-diagnostic system that can promptly identify any abnormal conditions. It also has strong computing power, capable of reading and writing programs, and follows various pre-set technical methods, transmitting control instructions to the CPU in a scanning form, executing corresponding operations in each cycle. The memory of PLC has properties equivalent to computer memory; it not only stores various information but also logic variables and programs [13,14]. Its memory structure includes system memory responsible for storing various system information, while user memory stores client operations, with complete isolation between them. Through sensors, input and output components can monitor and adjust the surrounding electronic devices.

3.2. Optimization of Harvesting Mechanical Arm Electrical Control System Based on Particle Swarm Algorithm

When harvesting robotic arms are collecting a large number of fruits, the order of their operations significantly affects their work efficiency. To address this issue, we can use intelligent algorithms to optimize the control system, enabling them to complete harvesting tasks more efficiently [15]. The particle swarm algorithm can extract the optimal solution from random particles and iteratively improve precision, not only within the algorithm itself but also for the entire population.

If we partition a D-dimensional search space into Ns! sets of particles, where the i-th particle represents a D-dimensional vector, then

$$X_i = \left(x_{i1}, x_{i2}, \cdots, x_{iD}\right) \quad (i = 1, 2, \cdots, N)$$

The motion mode of the i-th particle can be represented by a D-dimensional equation, namely

$$V_i = \left(v_{i1}, v_{i2}, \cdots, v_{iD}\right) \quad (i = 1, 2, \cdots 3)$$

This formula consists of three different components: the first component describes the motion model of an object; The second component describes the actual situation of the object; The third component describes the direction in which an object moves in different objects, that is, the process of the object moving in a more optimal direction. Through practical situations, we can define the values of these three components as c=c1=c2=D, where via refers to the

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velocity of the object, vi [vi1,. vimax], and max refers to a constant. Adopting a new particle swarm optimization algorithm with inertia weights and carefully designed, the results are as follows:

$$x_{ij}(t+1) = x_{ij}(t) + v_{ij}(t+1)$$

The purpose of Part 1 is to ensure perfect convergence of the entire particle set, while Parts 2 and 3 aim to ensure local optimal solutions. By setting the weight coefficient, we can achieve faster global convergence at higher u values, while at lower w values, we can achieve slower global convergence. According to our research, when w is within the range of [0.8-1.2], the convergence of the algorithm will be improved. However, when w exceeds w>1.2, it is difficult for the algorithm to achieve perfect global convergence. After multiple iterations, we can obtain the local or global optima of the particle swarm. This method is applied to the harvesting sequence of harvesting robots, which can help them complete harvesting tasks faster and is more conducive to the quality of harvesting. Please refer to Figure 1 for the specific operation method.

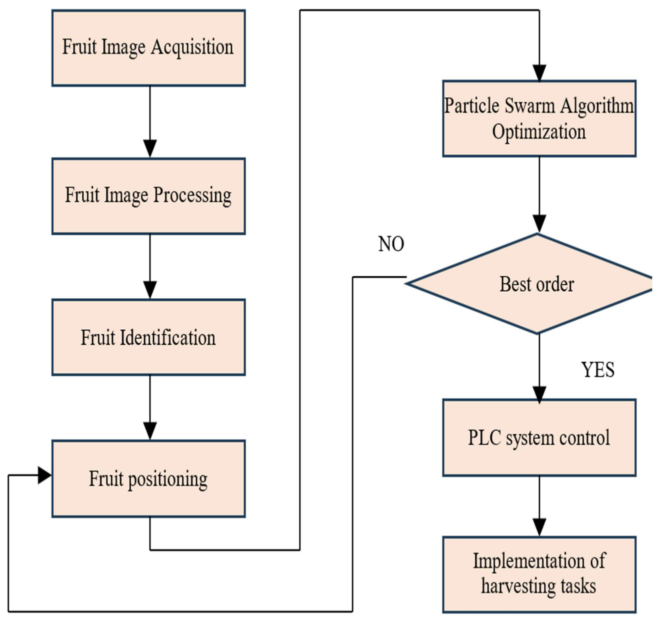

Figure 1. Shows a control process implemented using particle swarm and PLC technology

When using a robot to harvest fruits, it first collects and analyzes information about the surrounding environment and then operates using PLC. If a larger quantity of fruits needs to be harvested, it will utilize the particle swarm algorithm to optimize the harvesting process, obtaining a more efficient harvesting scheme. In this way, the harvesting tasks can be completed quickly and accurately based on the predefined harvesting process.

4. Experimental Design and Results Analysis

4.1. PLC Electrical Control System Experiment for Harvesting Robot

Through the application of the particle swarm algorithm, we validated the effectiveness of the PLC control system. Based on simulated actual working conditions, we constructed a basic framework for a harvesting mechanical arm, equipping it with various manipulative functions, including up and down, left and right, rotation, and others. Through programmed control, the robot can achieve multiple control functions, enabling it to interpret control signals sent from sensors, control signals sent from computers, and perform graphic processing based on the particle swarm algorithm. This allows the robot's control system to efficiently achieve automatic manipulation, thereby improving the accuracy and efficiency of harvesting. During the experiment, the PLC control system was established as the foundation for the mechanical arm's operations, setting various PLC control commands for sensors, switches, and more. The control commands were divided into two parts: input commands and output instructions. During the control of output commands, the control system can interpret input commands, perform manipulation in conjunction with the computer, and optimize the output command instructions. The PLC electrical control system's input-output mainly includes various sensor inputs, electromagnetic valve controls, and switch controls. The input stage focuses on collecting sensor positions, mainly including four groups of control commands (X1-X4), while the output stage includes various electromagnetic valve control commands, mainly consisting of four groups of control commands (Y1-Y4~Y1-Y4). The control system employs computer image processing to identify and locate fruit images and uses the particle swarm algorithm to arrange the harvesting sequence, which is then transmitted to the PLC control system to complete the harvesting tasks.

4.2. Result Analysis

Through a series of studies, we found that the use of the particle swarm algorithm can significantly reduce harvesting errors. The reason is that it can make more precise adjustments to the fruit's position based on specific algorithms, reducing the mechanical arm's mistakes and allowing for a more stable completion of the harvesting task, thereby greatly improving harvesting efficiency. Figure 2 demonstrates the reliability of this algorithm.

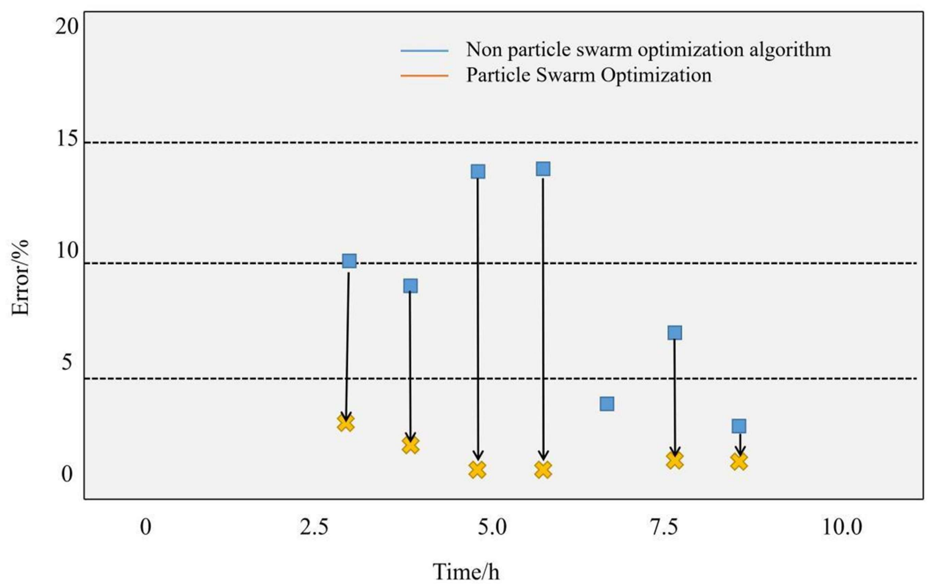

Figure 2. Error Statistics Results

Through research, we found that when we collect the same amount of green peppers, we choose to use particle swarm optimization to control their transportation during the collection process. We found that compared to not using this algorithm, we control the transportation distance during the harvesting process to be shorter and the harvesting efficiency to be higher. This discovery can be seen in Figure 2. By applying particle swarm optimization algorithm, the harvesting robot can arrange the harvesting time more orderly and achieve better work performance within a limited time, greatly improving work efficiency. The ultimate goal of this study is to enable the robotic arm to achieve high-precision handling operations. The most common mistake in handling operations is to place it on the material grabbing action of the I-shaped wheel. So, the key indicators for evaluating the robot control system are the success and accuracy of material grabbing, with the former referring to the ratio between the number of successful material grabbing and the total number of materials grabbing. Seize the work wheel experiment and locate a portion of the erroneous results in Figure 3.

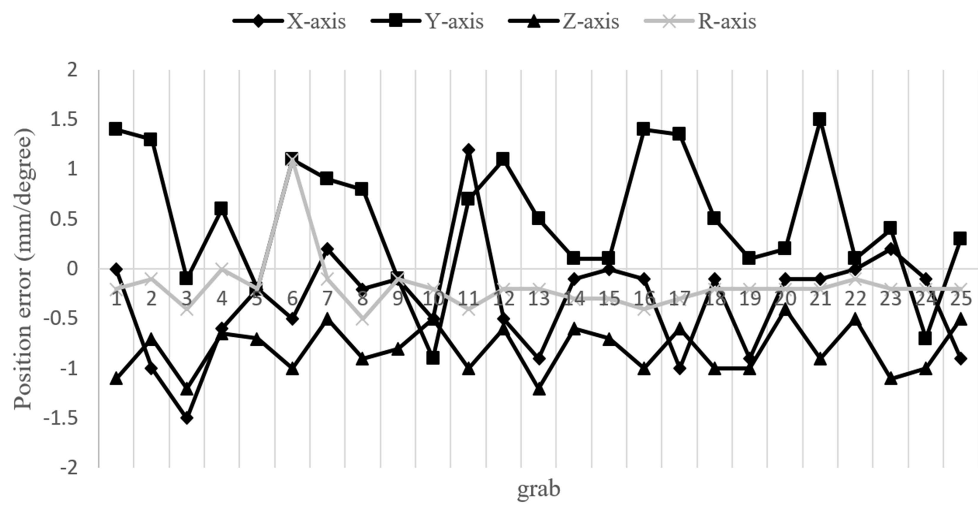

Figure 3. Positioning Error under Strong Light Conditions

Through 100 grabbing experiments on the pulley under strong light exposure, the experimental results are shown in Figure 3. The results indicate that the accuracy of the robot's designed mechanical hand in carrying out handling operations under strong light conditions exceeds 95%, meeting the design requirements. The experiments also verified that the control system is logically sound for each structural parameter and can perform handling operations to high standards. The horizontal axis in the graph represents the number of changes in the grabbing sequence, and the vertical coordinate represents the positioning error. Observing the change curve, the measured values of the forward and reverse rotation time are consistent with the theoretical value of 6 seconds. The overall measurement time for the pick-up and grab is also in line with the theoretical value of 12 seconds, implying that the system can achieve the intended goal of completing the task. Some errors occur, partly due to measurement errors and partly due to system errors. However, these errors still need to be corrected within the required range of accuracy.

5. Conclusions

By applying the particle swarm algorithm, we have significantly improved the electrical automation control of the harvesting robot, enabling it to possess stronger automation and better controllability. We integrated the particle swarm algorithm into the PLC control system and used it to control electrical components, ensuring stability under various working conditions. Our experiments have demonstrated that the particle swarm algorithm plays a crucial role in enhancing the harvesting process while maintaining good stability and workpiece quality. This finding provides valuable insights and recommendations for further improving the harvesting robot.

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