APPLICATION OF "WHEELED" INDEXING MECHANISM IN PACKAGING PRODUCTION LINE

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Abstract - This study introduces a novel intermediate indexing mechanism that addresses the dual needs of rhythm consistency and space saving in fruit packaging lines. The mechanism facilitates coordination among stations, improves connectivity, enhances overall efficiency, and reduces costs.To ensure the production line operates at the required cycle time, a roulette-type worm gear mechanism was designed and modeled in 3D software. Its motion is driven by a stepper motor controlled by a PLC S7-1200, while an incremental encoder provides closed-loop feedback to ensure rotational accuracy and reduce cost. Finally, circuit design and prototype experiments were conducted for validation. The results show that the 'wheeled' indexing mechanism has a good effect on the connection and cycle control between the fruit transportation packaging sorting and packaging stations. Conclusion: Through experiments, the effectiveness and necessity of the mechanism to control the cycle time of the production line are verified. It provides a certain theoretical basis and reference for the design requirements of similar production lines.

Keywords: Indexing mechanism, Beat control, PLC conveying, Precision control.

1. Introduction

Near the consumer end of the fruit industry, farmers face labor-intensive fundamental tasks such as sorting, categorizing, and packaging, which consume significant labor. To address the issues of high labor intensity in manual grading and packaging [1], low efficiency, fruit skin damage [2], large weight measurement deviations during collection, and inefficient grading [4], automated weighing and packaging lines have been developed for agricultural automation [5,6]. However, inconsistencies in cycle times between workstations often lead to low overall line efficiency, mismatched speeds among stations, and hinder processing efficiency. To ensure that each workstation in the automated line operates in harmony with an ideal cycle, buffer sections are introduced between workstations to implement pacing control. For transport buffering on horizontal or moderately sloped paths [7], common solutions include ribbed conveyor belts and continuous elevators, among others[8]. Such mechanisms are widely used in warehouse material handling, tea bag packaging, and fruit packaging, yet they typically require considerable space. In terms of disc-based mechanisms, Zhang Liang [9] implemented horizontal disc systems in canning lines, resolving instability and aesthetics in manual filling and hygiene issues in food processing. Gao Hai [9] integrated indexing discs into jujube pitting equipment, driven by a stepper motor, achieving an accuracy rate of about 9% through gear ratios. Focusing on disc precision control, Zhang Wei [10] improved a rack-and-pinion indexing turntable, utilizing gear engagement for automatic centering, ensuring precise positioning, with testing revealing a table positioning accuracy of 12" and repeatability of 3". Kairu Shao et al. [11] reviewed existing calibration methods for precision rotary tables. They proposed a novel optimization function and experimentally determined the optimal readhead distribution as a key parameter, thereby developing an economical solution for self-calibrating the tables' positioning errors. Analysis reveals that disc mechanisms are frequently incorporated into production lines or equipment, but their elevating functions are less common. In fruit packaging production lines, positioning accuracy merely serves as the foundation for the effectiveness of the wheel-type indexing mechanism, whose primary function is to coordinate the production rhythm of the line. Therefore, this paper proposes to adopt a vertical indexing disc for conveying and rhythm control, and puts forward a method of

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integrating the entire mechanism into a motor to control its rotation accuracy. The coordinated control of the wheel-type indexing mechanism over the production line rhythm is realized via PLC. Finally, experiments are conducted to verify the capability of the wheel-type indexing mechanism in controlling the production rhythm of the packaging line.

2. Mechanism Design

- ***Requirement Analysis***

The indexing mechanism is situated between the grading and packaging stations. The signaling system primarily relies on two sensors: an inlet sensor and a cylinder position sensor at the rear limit of the packaging station (which serves as the discharge sensor for the indexing station). These sensors jointly facilitate three key functions: determining the current count within the station, acting as input signals for other stations, and governing the process of the station's operation. The distribution of these three stations is illustrated in Figure 1.

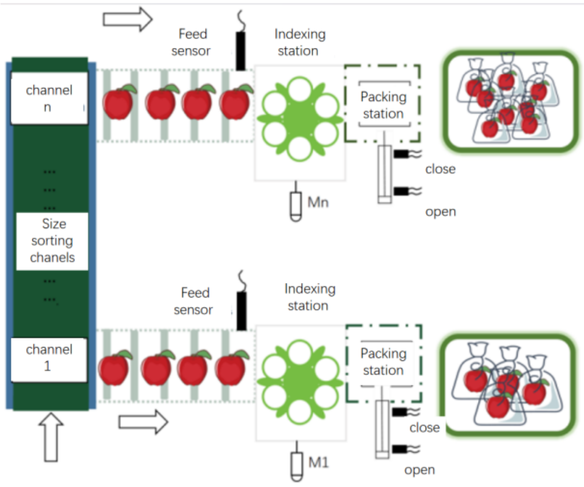

Figure 1: Schematic diagram of the production line process

The operational process and functional requirements of the production line, as depicted in Figure 1, are as follows:

(1) After passing through size grading, the fruits are conveyed by a belt to the lowest position of the indexing disc;

(2) The feed sensor signal is triggered, setting the sensor, indicating the workstation status as true.

(3) Check if the discharge port sensor status is true; a signal of true from the discharge sensor signifies the packaging station is ready for feeding.

(4) When the feed sensor is true and the discharge port sensor is also true, the motor initiates.

(5) After the motor starts, the indexing dial rotates by one indexing angle.

(6) If the count is not zero, the workstation must continue to expel stored materials, executing the material emptying function.

(7) The indexing mechanism is required to control the takt, regulate the feeding speed based on the current storage quantity in the indexing plate, and timely address material blockages simultaneously.

According to the functional requirements of the indexing station, its control can be categorized into four states: Initial State (S0), running (S1), stopping (S2), and cleaning (S3), with state encodings as shown in Table 1. I1.2 and I1.3 denote the input sensor signal and output sensor signal, respectively, and a flag M is set to determine whether the storage is empty. In this mechanism, a stepping motor is employed for angular control, with its real-time position represented by Act_Pos, the target angle by α, and the position corresponding to the target angle by Pos. Based on the principle of the stepping motor's operation, the stopping condition for the motor's rotation is when the real-time position Act_Pos reaches the position Pos corresponding to the target angle, as illustrated by Equation (1).

$$\text{Pos} = L * \frac{\alpha}{360} \tag{1}$$

Based on the coding status table and the program flowchart, the indexing station status diagram can be derived, as shown in Figure 2. For the buffer conveyor mechanism, it can only operate under the conditions that there is material at the inlet and no material at the outlet, or when the storage quantity is not zero.

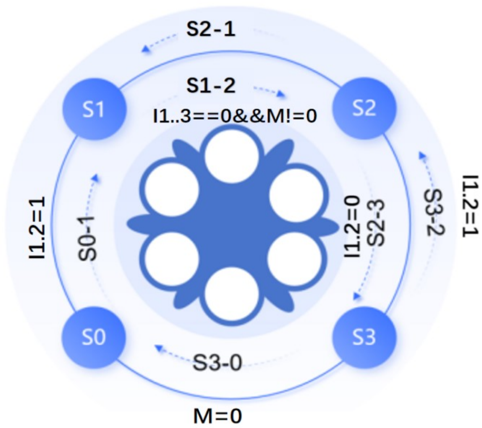

Figure 2: Analysis diagram of the state of the indexing mechanism

Table 1: Encoding status table

I1.2	I1.3	M	States	Explanation
0	1	0	S0	initial state
1	1	-	S1	running
-	0	-	S2	stopping
0	-	!0	S3	cleaning

- ***Structural Design***

(1) Selection of the Transmission System

The indexing mechanism for rhythm coordination requires a transmission system that meets two core demands. First, it must convert the high-speed rotation of the motor into low-speed, high-torque, and precisely controllable motion for the packaging actuator. Second, it must immediately lock the actuator during emergency stops or power failures to prevent fruits from falling and being damaged by gravity. The worm gear drive is particularly suitable in this context due to its high single-stage reduction ratio and reverse self-locking property.

(2) Design of Key Parameters

The objective of the indexing station is to ensure a utilization rate of >95% for the packaging station. The key parameter in the indexing mechanism is the number of storage positions N on the indexing table.

The upstream sorting unit has an average processing rate of 3 seconds per piece. Due to variations in detection complexity, the actual processing time fluctuates significantly. Based on actual working conditions, this can be modeled as a Poisson process. The arrival intervals follow an exponential distribution with a mean of $\lambda^{-1}=3$ seconds. The downstream packaging unit has a fixed cycle time of $\mu^{-1}=4$ seconds per piece. Assuming the buffer capacity on the indexing table is N, the system load is calculated as follows:

$$\rho = \lambda / \mu = (1/3)/(1/4) = 4/3 \tag{2}$$

The calculated utilization factor ρ exceeds 1, indicating that the upstream process is, on average, faster than the downstream process. Without a buffer, this would cause continuous accumulation at the downstream stage and eventually block the upstream stage. A finite buffer can stabilize the system. The M/M/1/K formula was applied:

$$P_0 = \frac{1-\rho}{1-\rho^{N+1}} \tag{3}$$

The downstream idle probability P_0 was calculated for different buffer capacities. When the buffer capacity N=6, the downstream idle probability is approximately 5.14%, corresponding to a utilization of about 94.86%, which is close to the target. Considering that the downstream packaging time is deterministic, the actual utilization will be higher than this approximation. Therefore, the buffer capacity was set to 6.The mechanical structure model was established as shown in Figure 3.

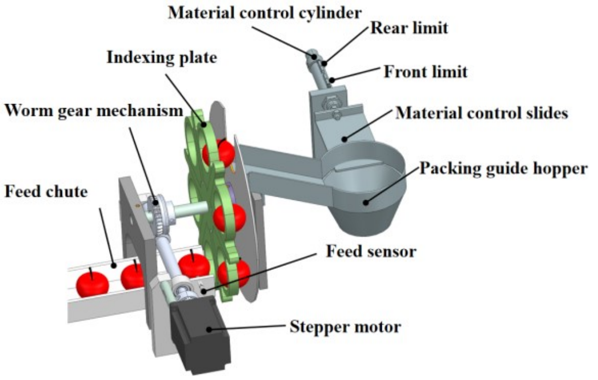

Figure 3: Indexing mechanism model

When the indexing mechanism operates on the production line, it is necessary to ensure positioning accuracy to prevent damage to the fruits during feeding and discharging. Therefore, the error conditions from input to output of the mechanism should be considered, and errors should be reduced when controlling the rotation of the indexing plate to ensure positioning accuracy[12].

- ***Position Control***

The mechanism employs a worm and worm gear drive, where errors in worm gear transmission including transmission errors, assembly errors, structural errors, and operational errors, can all impact the working precision of the equipment, thereby affecting its operational outcomes[1315]. Additional sources of error include geometric errors in the mechanical setup [16], wear [17[18], and step loss in stepper motors [19].

Accumulated errors can be mitigated through initialization, but the mechanical structure can only be initialized when the storage count equals zero during operation, necessitating alternative solutions to address motor errors. This complexity is compounded by the limitations of measurement tool precision and the rounding-off of parameters, such as actual rotational angles. Therefore, a simpler yet effective control strategy was adopted. The decision is made to encapsulate the entire mechanism into a feedback-equipped "motor" unit, leveraging an encoder to transmit high-precision shaft rotation data to the PLC [20]. The PLC then adjusts the motor's operation accordingly, effectively compensating for hardware inadequacies.

In this study, a stepper motor is employed for motor control; however, conventional methods do not effectively govern the positioning precision of the entire mechanism. Moreover, the stepper motor driver does not meet the criteria for implementing full closed-loop control in a servo manner. Consequently, a PLC-based full closed-loop control approach is adopted in this research to overcome these limitations.

The PLC-based full closed-loop control system integrates an external encoder to the PLC port, operating fundamentally by comparing the actual position feedback from the external encoder against the preset target position. This system first utilizes the PID control algorithm within the PLC to process the acquired information. Based on the PID calculation results, the output is adjusted to finely regulate the servo motor speed. This process enables precise closed-loop control throughout the entire equipment positioning cycle. The interconnections among these components are depicted in Figure 4.

During actual control execution, the encoder acquires the real-time status of the motor and relays it to the PLC, where a pre-programmed PID function block calculates the incoming data. Here, the PID computation addresses the mechanical errors of the mechanism. The data processed by the PID block is then forwarded to the Motor FB (Function Block), which commands PLC's output interface Q0.1 to generate control pulses, subsequently directing the stepper motor driver to control the stepper motor. This establishes a complete PLC-based closed-loop control system. The specific configuration of this closed-loop control is illustrated in Figure 4.

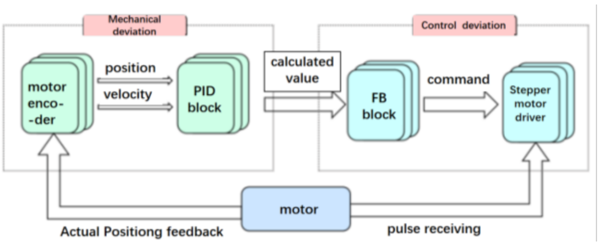

Figure 4: Wheeled indexing mechanism full closed-loop control schematic diagram

- ***Beat Control***

The main faults prone to occur in the production line are discharging faults and material blocking faults. A discharging fault refers to the situation where the speed of the next workstation of the buffer station decreases, causing fruits to fail to be output from the indexing plate in a timely manner. A material blocking fault refers to the situation where the speed of conveying fruits to the indexing plate is too fast, leading to material blocking at the feeding position. When the number of fruits at the feeding position is maintained at 2 or less, it is considered that there is no material blocking. When the number exceeds two, the feeding speed will be immediately reduced to prevent blocking.

According to the control requirements, after the indexing mechanism is installed in the production line, it needs to cooperate with the front and rear workstations. The control process of the indexing mechanism is shown in Figure 5. The six positions on the indexing plate are numbered and recorded. During operation, the current material receiving position and the states of the remaining positions are recorded, so as to effectively utilize the buffering function of the indexing plate to solve fault problems when faults occur.

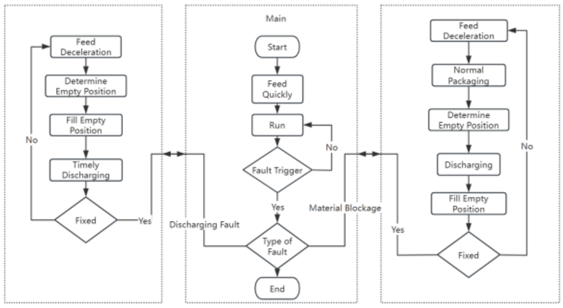

Figure 5: Flowchart of beat control

3. Assembly and Experimental Verification

- ***Assembly***

There may be a certain eccentric error in the connection between the encoder and the drive shaft [21].To ensure maximum concentricity between the encoder shaft and worm wheel shaft during assembly, an encoder bracket was designed based on the encoder step positioning dimensions and the three-hole positioning dimensions, as shown in Figure 6. Corresponding threaded holes are tapped on the worm wheel support plate. During design and manufacturing, the upper and lower holes of the bracket, the locating holes for bracket connections, the circular center of the worm wheel support plate's three positioning holes, are all referenced to the worm wheel shaft center as the datum.

Building upon the structure depicted in Figure 3 (The indexing mechanism model diagram), the encoder is mounted and connected to the worm wheel shaft, as illustrated in Figure 6. To validate the effectiveness of the design and meet requirements for high efficiency and jam-free operation, a prototype, as shown in Figure 7, was constructed. The prototype features a lifting height of 300mm and a distance of 65mm between the indexing disk and the backboard.

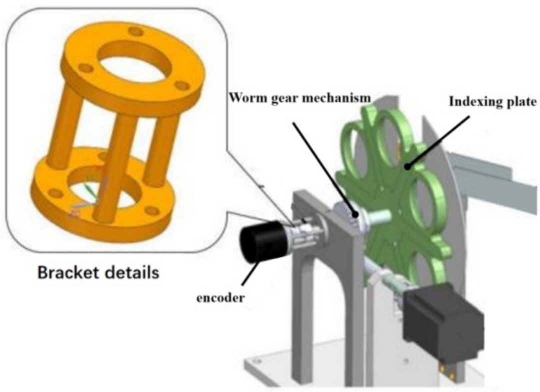

Figure 6: Improvements to the model

Figure 7: Physical prototypes

- ***Positioning Accuracy Measurement***

The system initialization was performed by establishing the zero position via the encoder Z-phase signal and locking the indexing turntable. The indexing angle was set to 60°, and basic functionality was verified. Subsequently, the positioning accuracy, repeat positioning accuracy, and backlash of the indexing table were measured using a laser interferometer system. Five target angles were selected for measurement, with each angle measured 10 times and the average value taken. A 5-minute cooling period was implemented after each measurement to minimize thermal drift error. The results are summarized in Table 2.

Table 2: Prototype test data of wheeled indexing mechanism

Group	Target Angle (°)	Positioning Accuracy (″)	Repeat Positioning Accuracy (″)	Backlash (″)
1	30	35	3	6
2	45	42	4	7
3	60	38	4	7
4	90	45	5	8
5	120	40	4	7

Through measurement, the average positioning accuracy of the indexing mechanism is 40″, the repeat positioning accuracy is 4″, and the backlash is 7″.

- ***Beat Control Experiment***

The feeding speed is set at 1.6 pieces per second, and the packaging speed of the subsequent packaging station is 1.2 pieces per second. The rotation time of the indexing plate is set to 1 second to ensure the timeliness of position replenishment. During production, to prevent material blockage, the feeding speed is adjusted in a timely manner based on the beat of the packaging station. The feeding speed fluctuates around the screening speed.

The production line was started and operated to record the changes in feeding speed, the utilization rate of the dial space position, the material blocking time, and the effective transmission quantity, so as to obtain a reasonable value of the production line cycle. It is set that when the number of fruits in the dial is 3 and the number of fruits at the feeding port is greater than 2, blocking occurs, and the blocking time begins to be recorded until the blocking is eliminated. Multiple 1-minute tests were carried out, and the results of the feeding speed changes are shown in Figure 8. The corresponding changes in the number of fruits at the feeding port are shown in Figure 9.

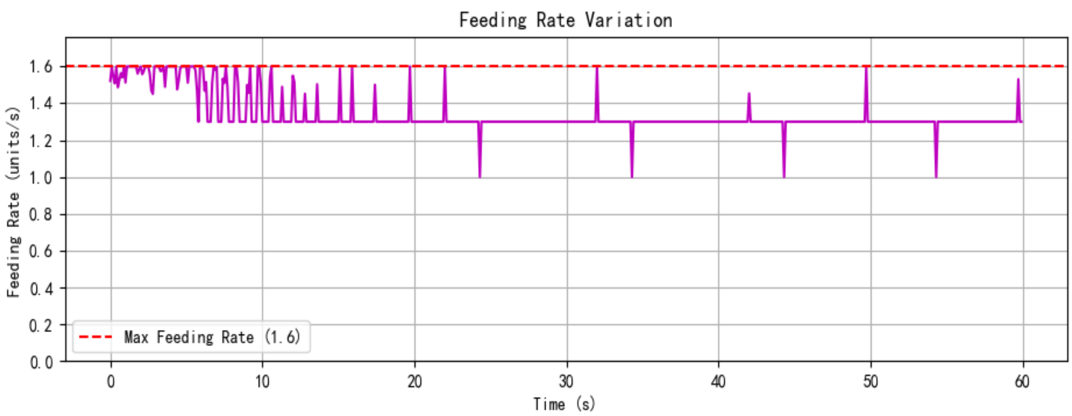

Figure 8: Feeding speed variation

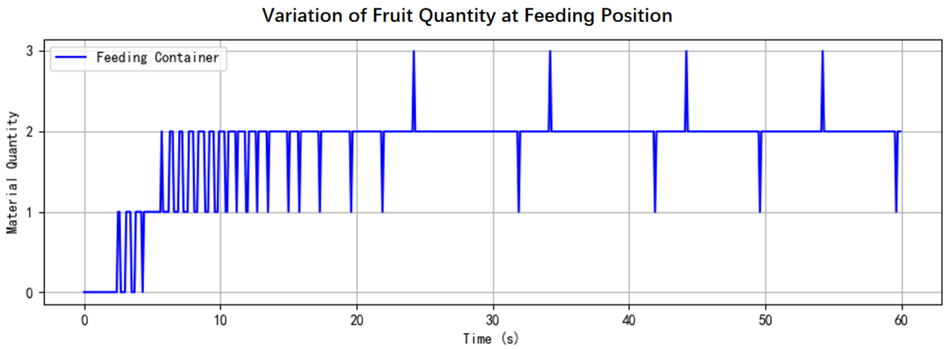

Figure 9: Variation of fruit quantity at feeding position

Data within multiple production time periods were recorded as shown in Table 3. During normal operation, the system maintained an average feeding speed of 1.33 pieces per second and an effective transmission speed of 4,668 pieces per hour.

The average handling time for operational interruptions was 10.3 seconds for the maximum material blockage and 6.3 seconds for replenishment.

Table 3: Transmission performance record table

Group	Feeding Beat (pcs/s)	Longest Material Blocking Time (s)	Effective Transmission Quantity (pcs)	Average Replenishment Time (s)
1	1.3	10	4677	6
2	1.35	8.7	4652	6.5
3	1.32	11	4662	6.3
4	1.35	10.7	4670	6
5	1.3	8.8	4673	6.5
6	1.34	8.5	4668	6.5
7	1.3	13	4672	6.4
8	1.32	11.6	4670	6

Interferences were added during operation to verify the production line's response time for handling material blocking and material shortage. Due to factors such as untimely manual feeding, production parameters fluctuate, leading to the occurrence of material blocking and discharging failures.

The response and processing times of the production line for the two types of failures were continuously recorded for 12 consecutive failures, as shown in the Figure10. The average processing time for discharging failures was 20.08 seconds, and the average processing time for material blocking was 13.25 seconds.

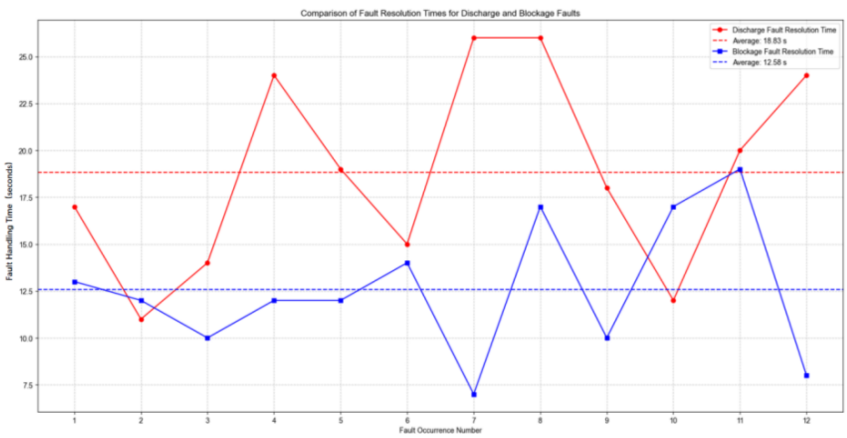

Figure 10: Line chart of fault handling capability

Based on the experimental results, the production line with the indexing mechanism added can effectively transport fruits. Meanwhile, it has the coordination ability in dealing with material blocking and discharging failures, and can control the material blocking time within 1 minute, ensuring the effective progress of production.

4. Conclusions

This paper presents a wheel-type indexing mechanical structure designed to use worm gear transmission. A 3D model of the wheel-type indexing mechanical structure was established, and the entire mechanical structure was packaged as a motor with feedback signals to control errors. The system is controlled by a PLC program, and functional verification was conducted on a test prototype. Through production experiments, the coordination effect of the wheel-type indexing mechanical structure on the production cycle of the packaging line was analyzed. The results demonstrate that the wheel-type indexing mechanism effectively connects the sorting and packaging stations for fruits of varying sizes. It successfully coordinates the cycle time among stations within the fruit screening and transportation production line. The system achieves a fruit conveying speed of approximately 4,668 pieces per hour. Key handling time metrics include an average discharge fault resolution of about 20.08 seconds and an average material blockage clearance of around 13.25 seconds. This effectively prevents material blockage, mutual extrusion, and other issues between workstations in the production line.

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