Improvement of Palletizing Robot’s Clamp Device for Cigarette Products

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Abstract. In order to reduce the drop number of cigarette packing cases and downtime during the robot palletizing, and improve palletizing efficiency, the key technology of the robot’s clamp device was improved. The improvement techniques included vacuum suction cups specification optimizing, suction cups horizontal and vertical balancing layout, robot running smoothly, increasing the intake pipe, multi-loop vacuum generator. These techniques were applied to KUKA KR150L 150/3 robot, tested on normal and circular cigarette packing cases such as Yuxi (Hard Harmony) brand produced by Yuxi cigarette factory. The results showed that the improvement of robot palletizing cigarette packing cases is stable, and the average drop number is reduced to 13/month from 123/month before improvement, the number of downtime is reduced to 14 times/month from 125 times/month, the equipment efficiency is improved to 9.6 /min. The improvement can provide technical support for the stable operation of the robot palletizing cigarette cases.

1. Introduction
Palletizing robot is the key equipment of automatic logistics system for cigarette products in tobacco industry. As an important part of palletizing robot, the clamp device, its execution ability, reliable performance, shape size and so on have important influence on the whole palletizing of cigarette packing cases [1-2]. The palletizing robot works by means of clamp device adsorbing the surface of cigarette packing case. Due to transportation, storage and other reasons, the surface of the case is uneven, there are dust impurities and other problems [3–5], its compressive strength and surface flatness are reduced, cases is not adsorbed firm and fall down. So the cigarette and case are damaged, causing certain economic loss. In addition, dealing with falling and broken cigarette packing case leads to increased labor intensity and reduced productivity. Therefore, in order to complete the efficient and high quality cigarette packing case recycling, reduce their drop number, and improve the production efficiency, the robot's clamp device has been proposed for higher adaptability [6].

In recent years, there have been many researches and improvements on robot's clamp device. Su Yazhong [7] had improved the negative pressure pipeline, suction cup and negative pressure solenoid valve in the absorbing device of the case. Ma Liang [8] et al. used planar sponge suction cup, set up a special palletizing procedure, adjusted precisely the position of the clamp device to catch the case,
reduced the gas supply impurities by use of oil-water separator, and reduced the robot running speed and other methods. Reduced the drop number of cigarette packing cases, and improved production efficiency. Miao Dengyu [9] et al. used pneumatic drive and vacuum adsorption principle to design a robot grasping device. It could grasp a variety of forms of materials, and successfully realized the handling, stacking and other actions. Mohsen Moghaddam [10] et al. built a parallel framework by studying the parallel pickup and placement (PPNP) problem, and optimized the multi-gripper robot arm, but did not precisely optimize the gripper end. AnnaValente [11] et al. proposed a robot motion model based on smooth running trajectory, which optimized the motion time minimization and improved the motion stability of the joint. The improvement results of suction cups, stable negative pressure, parallel design and smooth trajectory mentioned above have reference significance. Therefore, the key technologies such as suction cup and negative pressure of palletizing robot's clamp device are improved to reduce the drop number of cigarette packing cases and downtime in the palletizing operation of robot, so as to improve the palletizing robot efficiency.

2. Problem description

2.1. Working principle

The structure of palletizing robot's clamp device before the improvement is mainly composed of solenoid valve, vacuum generator, square vacuum tube, suction cups, lifting bracket, vacuum pressure detector and other components, as shown in Fig.1. The structure of clamp device takes the lifting bracket (the sixth axis of the robot) as the main body. The lower part of the body is equipped with a backboard of suction cups, which is used for installing square vacuum tube, suction cups, spring and other parts. The upper part is provided with the backboard of vacuum generator, which is used for installing solenoid valve, vacuum generator, vacuum pressure detector and other components. The lifting bracket, the backboard of suction cups and the backboard of vacuum generator are all provided with holes to facilitate the connection of the gas pipes and connectors to the main components after passing through [12]. When the device works, the solenoid valve is opened after the cigarette packing cases are in place, and the compressed gas is supplied to the vacuum generator. The gas pressure at the outlet of the vacuum generator is lower than atmospheric pressure, which produces negative pressure. Suction is generated through the suction cups. At the same time, the robot moves, presses and draws cases. The spring can ensure that the clamp device can adapt to the case plane and relieve the pressure. During the working of the device, if the suction cups leak and the cases fall off, and the vacuum pressure detector detects that the negative pressure does not reach the set vacuum degree, then the robot stops running.
2.2. Problem analysis

Cigarette packing cases, especially the circular cigarette packing cases, because of their surface uneven, or slight scratches, tiny holes, dust impurities, etc., robot's clamp device is easy to cause suction leakage, negative pressure reduction, resulting in insufficient suction caused the cases fall. The main causes of cigarette packing cases falling are:

a) The suction cups have small area and their suction force is insufficient. The calculation formula of suction force is as follows [13]:

\[ W = PA \]  \hspace{1cm} (1)

Where, \( W \) is the suction force, N; \( P \) is the vacuum degree (relative pressure, MPa) of suction cups, which are within 63% ~ 95% of the maximum vacuum degree. \( A \) is the effective adsorption area of the suction cups, mm².

As in equation (1), it can be seen that when the suction cups specification are selected, if the total effective area of the suction cups are small, the suction and lifting force is low and the cases are easy to fall off.

b) The layout of the suction cups is unreasonable, and the pressure of the cases is easy to be out of balance. Before the improvement, the layout of the suction cups adopted large-diameter suction cups to form a longitudinal layout of 3 groups with 5 suction cups in each group, as shown in Fig. 2. If the suction and lift force of group 1 or group 3 is lost due to suction cups leakage, the longitudinal force will be unbalanced and the cases will fall off.

c) In the process of grasping the cases, the robot's clamp device increases the speed too much, which puts forward a higher demand for the suction force. Meanwhile, the acceleration passing through the large performance is shown as the rapid start and stop during the robot operation, and the cases fall due to the large swing amplitude. The theoretical maximum adsorption force (suction and lifting demand) is calculated as follows:

\[ F = m(g + a/\mu)s \]  \hspace{1cm} (2)

Where, \( F \) is the theoretical maximum adsorption force, N; \( m \) is the mass of each cigarette packing case (kg); \( g \) is the acceleration of gravity, m/s²; \( a \) is the running acceleration, m/s²; \( \mu \) is the surface coefficient (0.6 for rough surface); \( s \) is safety factor (coefficient of breathable material or rough surface is 2).

As in equation (2), parameters \( m \), \( g \), \( u \) and \( s \) cannot be changed, and the higher the running acceleration \( a \) is, the higher the suction and hoisting demand is. When the suction lift demand is close to the suction lift force \( (F=W) \), the case is easy to fall.

d) The small sectional area of the inlet pipe of the vacuum generator leads to the unstable working pressure of the compressed gas. According to Bernoulli equation [14], it can be known that:
In equations (3) and (4), \( A \) is the sectional area of the pipeline, m\(^2\); \( v \) is the flow velocity, m/s; \( P \) is static pressure, Pa; \( \frac{1}{2} \rho v^2 \) is the fluctuation value of system working pressure (dynamic pressure), where \( \rho \) is the gas density, kg/m\(^3\).

It can be seen from Fig.3 and equations (3) and (4) that in order to achieve the predetermined vacuum degree, the working pressure of compressed gas supplied to the vacuum generator, \( P_0, v_0 \) and \( A_0 \) (determined by the vacuum generator specifications), are constant.

![Bernoulli principle application schematic](image)

**Figure 3.** Bernoulli principle application schematic

Now, if \( A_x \) is too small, then \( v_x \) needs to be increased; If \( v_x \) is increased, the dynamic pressure \( \frac{1}{2} \rho v^2 \) increases. Therefore, when the sectional area of the inlet pipe of the vacuum generator is small, the operating pressure of the compressed gas of the vacuum generator fluctuates greatly, resulting in unstable vacuum and easy fall of the cases.

e) The vacuum circuit design is unreasonable. As shown in Fig.4, the vacuum circuit before the improvement is a single circuit, including 2 vacuum generators and 3 groups of suction cups. Both vacuum generators can act on 3 suction cups, and produce double adsorption force to the case. However, the 3 suction cups of the single circuit are connected with each other. When one of the suction cups leaks, the vacuum degree \( P \) is not up to the requirement. At this point, the case has no other circuit to provide suction and lift force, thus falling.

![Working principle of vacuum circuit before improvement](image)

**Figure 4.** Working principle of vacuum circuit before improvement
3. Improvement

3.1. Device structure
After the improvement, 117 φ30 vacuum suction cups are selected for the clamp device of palletizing robot, the CONT Approximation approach instruction [15] is loaded in the robot action, the inlet pipe and air valve specifications are increased, the five-loop independent working vacuum generator is adopted, and the suction cups are divided into five groups for horizontal and horizontal balanced layout. The case drop detector is changed from a vacuum pressure detector to a photoelectric sensor, as shown in Fig. 5.

![Diagram of robot's clamp device after improvement](image)

1. Solenoid valve 2. Vacuum generator 3. Silencer 4. Gas pipes and connectors 5. Square vacuum tube 6. Suction cups 7. Backboard of suction cups 8. Spring 9. Lifting bracket 10. Photoelectric sensor 11. Backboard of vacuum generator

**Figure 5.** Structure decomposition diagram of robot's clamp device after improvement

3.2. Improvement details

| Specifications-D/mm | Effective diameter /mm | Layout mode/(horizontal × vertical) | Effective area-A/mm² | Suction force-W/N |
|---------------------|------------------------|-------------------------------------|----------------------|-------------------|
| φ15                 | 12                     | 19×26                               | 55 841.76            | 3 518.03          |
| φ30                 | 25                     | 9×13                                | 57 403.13            | 3 616.40          |
| φ40                 | 32                     | 7×10                                | 56 268.80            | 3 544.93          |
| φ55                 | 44                     | 5×7                                 | 53 191.60            | 3 351.07          |
| φ75                 | 60                     | 3×5                                 | 42 390.00            | 2 670.57          |
| φ100                | 85                     | 2×4                                 | 45 373.00            | 2 858.50          |
| φ125                | 105                    | 2×3                                 | 51 927.75            | 3 271.45          |

a) Vacuum suction cups specification optimizing. In order to increase the suction force, we need to increase the suction area. Under the constraint of the size of the backboard of suction cups, the vacuum suction cups specification is optimized to maximize the total effective area of all the suction cups. Given that the horizontal and vertical dimensions of the backboard are 290 mm×400 mm, the NBR suction cup...
of Festo is selected to compare the total effective area when it is laid out on the backboard, so as to obtain the maximum suction and lifting force. It can be seen from Tab.1 that the maximum effective area $A=57403.13\text{mm}^2$ will be obtained by selecting φ30mm suction cup, at which point the suction force $W=3616.40\text{N}$.

b) Suction cups horizontal and vertical balancing layout. After the improvement, the vacuum suction cups adopt the specification φ30, a total of $9\times13=117$ cups, divided into 5 groups, the layout of which is shown in Fig. 6. Only when group 1, 3, 4 and 5 were working alone, the force imbalance was large. In most cases, the horizontal or vertical adsorption force balance could be maintained, thus reducing the drop number of cigarette packing cases.

![Figure 6. Suction cups arrangement after improvement](image)

c) Robot running smoothly. The process of palletizing cigarette packing cases by robot is as follows: the robot draws cases at P1, lifts them to P2, transfers them to P3, and places them at P4 to complete the cases palletizing, as shown in Fig. 7. After the robot runs with the cases load, it will stop and start in a hurry at the switch point before the next. The acceleration is large, and the cases will swing and fall. Therefore, the "CONT" instruction is inserted into the program statement to command the robot not to precisely run to the switching point, but to smooth the transition to that point. This method is called "approximation method", which reduces the number of the cases drops and improves the robot's operation efficiency.

![Figure 7. Schematic diagram of approximation approach trajectory](image)

After the improvement, the running acceleration of the robot $a=1\text{m/s}^2$, the robot speed can be increased to 80% of its full speed.

The mass of a cigarette packing case is 15.2 kg. According to equation (2), the theory maximum adsorption force (suction and lift demand) is $F=15.2\times(9.8+1\times80%/0.6)\times2=338.35\text{N}$, and the suction force is $W=3616.40\text{N}$. The suction force is far more than the suction lift demand, the operation is more reliable.
d) Increasing the intake pipe. Increasing the diameter of the intake pipe can reduce the airflow velocity, thus reducing the fluctuation of operating pressure of the system and maintaining the stable vacuum. FestoVAD-3/8 vacuum generator is selected. According to the production requirements, if the vacuum degree of 0.063mpa is needed, the flow should reach 13 L/min, and the working pressure of compressed gas should reach above 0.4 MPa (the maximum vacuum degree of the vacuum generator is 0.083 MPa, and the working pressure of compressed gas is 0.6 MPa). The Laval diameter of the vacuum generator is 1.5mm. According to Tab. 2, the first and second intake pipes can be increased from φ10 and φ8 to φ12 and φ10 respectively, and the solenoid valve Festo MFH - 3-1/4 can be changed to large-size MFH - 3-1/2.

| Intake pipe specification /mm | Inner diameter / mm | Airflow velocity / (m·s⁻¹) | Fluctuation value of system working pressure (dynamic pressure)/Pa |
|------------------------------|--------------------|-----------------------------|---------------------------------------------------------|
| φ8                           | 5.9                | 7.92                        | 60.22                                                   |
| φ10                          | 7.0                | 5.63                        | 20.44                                                   |
| φ12                          | 8.4                | 3.91                        | 9.86                                                    |

e) Multi-loop vacuum generator is used. Referring to the analysis method of parallelism [10], the improved vacuum loop structure adopts a five-loop vacuum generator, and a vacuum generator and a square vacuum tube, air pipes, joints and suction cups constitute a loop, as shown in Fig 8. After the improvement, each circuit works independently. When one set of suction cup leaks, its vacuum generator loses its adsorption effect due to air leakage, but the other vacuum generators work normally. As long as the cigarette packing cases bears a balanced force, the cigarette packing cases falling times can be avoided or reduced. At the same time, the photoelectric sensor is used instead of the vacuum pressure detector, which can determine whether the cigarette packing cases has fallen by detecting the vacuum degree. The detection is more accurate.

![Figure 8. Working principle of vacuum circuit after improvement](image_url)

1. Solenoid valve 2. Vacuum generator (including silencer) 3. Suction cups 4. Cigarette packing case

4. Application effect

4.1. DOE

Materials: The cigarette brand of normal and circular cigarette packing cases such as Yuxi (hard harmony), Hongtashan (hard classic), Hongtashan (soft classic), Hongtashan(hard classic 100), Hongmei (hard spring), Hongmei (soft shun) [provided by Hongta tobacco (group) co., LTD. Yuxi cigarette factory].

Equipment: 15 robots of KR150L 150/3 (KUKA, Germany).
Methods: there were 15 palletizing robots in the factory. They were used to palletizing normal and circular cigarette packing cases with different specifications of cigarette products. The drop number of cigarette packing cases was counted and averaged 3 months before and after improvement.

Before the improvement, the speed of palletizing robot was 60% of the full speed, and after the improvement, the speed of the palletizing robot was 80% of the full speed. The shutdown times of the palletizing robot were counted and the palletizing efficiency of the palletizing robot was calculated.

4.2. Data analysis
As can be seen from Tab. 3, the drop number of the normal cigarette packing cases before and after the improvement decreased from 40 /month to 3/month, and the drop number of the circular cigarette packing cases before and after the improvement decreased from 83 /month to 10/month. All of the drop number decreased from 123 /month to 13/month, a decrease of 89.4%. The problem of falling circular cigarette packing cases has been greatly improved.

| Serial number | Drop number (normal case) | Drop number (circular case) | Total | Drop number (normal case) | Drop number (circular case) | Total |
|---------------|---------------------------|-----------------------------|-------|---------------------------|-----------------------------|-------|
| 1             | 38                        | 91                          | 129   | 3                         | 16                          | 19    |
| 2             | 42                        | 76                          | 118   | 2                         | 6                           | 8     |
| 3             | 40                        | 83                          | 123   | 4                         | 7                           | 11    |
| Average       | 40                        | 83                          | 123   | 3                         | 10                          | 13    |

As can be seen from Tab. 4, the robot performance has been greatly improved. In order to ensure the stability of palletizing before the improvement, the speed rate of robot was adjusted to less than 60% of the full speed. The down times of palletizing robot was 125 times/month, and the palletizing efficiency was lower than 7.2 /min. After the improvement, the rate of the robot can be adjusted to 80%, the downtime is reduced to 14 times/month, and the palletizing efficiency is 9.6 /min.

| Palletizing robot | Palletizing speed rate (%) | Down times (times·month⁻¹) | Palletizing efficiency /min |
|-------------------|---------------------------|-----------------------------|----------------------------|
| Before the improve| 60                        | 125                         | 7.2                        |
| After the improve  | 80                        | 14                          | 9.6                        |

5. Conclusion
According to Bernoulli and the principle of multi-thread parallel guarantee, the palletizing robot’s clamp device is improved. By optimizing the vacuum suction cups specification, balancing the suction cup layout, loading the robot smooth action instruction, increasing the intake pipe, adopting the multi-loop vacuum generator, the problem of the high drop number of cigarette packing cases and many times of stop of palletizing robot is solved, and the palletizing efficiency is improved. The improved KUKA KR150L 150/3 robot was used to palletize the normal and circular cigarette packing cases such as Yuxi (Hard Harmony) brand for testing. The results showed that: After the improvement, the speed rate of palletizing robot can be adjusted to 80% of the full speed. the drop number of normal cigarette packing cases is reduced by 37 /month, and the drop number of circular cigarette packing cases is reduced by 73 /month, the total drop number is reduced by 110 /month, the downtime is reduced by 111 times/month, the palletizing efficiency is improved by 2.4 /min, and the palletizing robot runs stably.

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