A Novel Continuous Single-Spindle Doffing Robot with a Spatial Cam and Multiple Grippers

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Abstract. Doffing machines for ring spinning machines include single-spindle doffers and group doffers. Group doffers are efficient but complex and expensive to build. Present single-spindle doffers are easy to build and low in cost, but it contacts and hurts yarns in cops and even damages spindles after a long ride. This paper developed a novel continuous single-spindle doffing robot with a spatial cam and multiple grippers for ring spinning machines, called the SCMG robot. The SCMG robot mainly consists of a doffing device, a moving and locating device. The doffing device is composed of 14 grippers moving along a fixed 3D trajectory of a spatial cam. The moving and locating device adopts a positioning wheel meshing with the bottom of spindles. The mechanism principle, structure and force analysis of the SCMG robot are introduced in detail. Experimental results show that the SCMG robot can pull the cops out of the spindle vertically one by one. The grippers grasp the top of the cops without contacting the yarn. The SCMG robot is highly efficient and reliable.

Keywords: Doffing robot · Continuous single-spindle doffer · Spatial cam · Gripper · Ring spinning machine

1 Introduction

Ring spinning is a useful and important technology. During the ring spinning process, the operator needs to doff the cops of ring spinning machines. Currently, the doffing operation in over 60 % of the spinning corporations is accomplished by manual [1], shown in Fig. 1a. Automation of doffing operation is significant to the spinning industry with the rising of labor cost. Generally, doffing machines for ring spinning machines include single-spindle (or wagon) doffers and group doffers.

Group doffers, shown in Fig. 1b, have a high degree of automation and high production efficiency. However, the large cost limits their development. Group doffers have to be fixed to the frames of ring spinning machines, respectively. One group doffer can only serve one ring spinning machine. It is inevitable to modify the original spinning system largely in order to install group doffers on conventional ring spinning machines.

The common features of wagon doffers include low manufacture cost, simple structure, low energy levels, high efficiency and more. Different from group doffers, wagon doffers do not need to be fixed to the frames of ring spinning machines and can move

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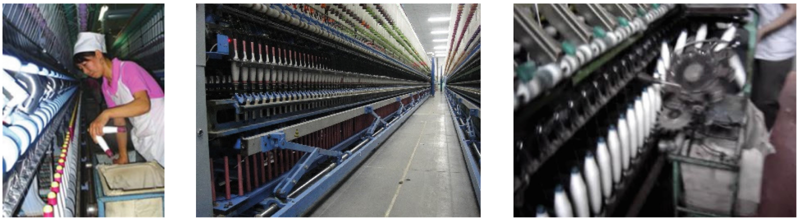


(a) Manual doffing (b) Group doffer (c) Double-disc doffer

Fig. 1. Doffing types of ring spinning machines

flexibly. Wagon doffers move along the rails of ring spinning machines only during the doffing process, so one wagon doffer can serve several ring spinning machines. A wide range of wagon doffers are developed since 1950s [2–6]. Double-disc doffer is a typical representative of them [7], as shown in Fig. 1c. Double-disc doffer doffs single cops every time and can achieve continuous doffing. The doffing efficiency of double-disc doffer is very high. But in the doffing process, the double discs will contact the yarn and damage spindles. Recently, some novel wagon doffers are developed [8, 9]. Most of them adopt the structure of the orthogonal coordinate robot. During the doffing process, these wagon doffers doff several cops (about 10 cops) at the same time and can pull the cops out vertically without contact with the yarn.

Group doffers are efficient but complex and expensive to build. Present single-spindle doffers are easy to build and low in cost, but it contacts and hurts yarns in cops and even damages spindles after a long ride.

This paper developed a novel continuous single-spindle doffing robot with a spatial cam and multiple grippers for ring spinning machines, called the SCMG robot. The SCMG robot mainly consists of a doffing device, a moving and locating device. The doffing device is composed of 14 grippers moving along a fixed 3D trajectory of a spatial cam. The moving and locating device adopts a positioning wheel meshing with the bottom of spindles. The SCMG robot combines the advantages of the double-disc wagon doffer and the group doffer. On one hand, the SC robot works with single-spindle and continuous doffing, which is helpful to promote doffing efficiency. On the other hand, the SCMG robot can pull cops out of spindles vertically. During the doffing process, the gripper of the SCMG robot grasps the top of cops without touching yarns.

2 Principle and Structure of the SCMG Robot

2.1 Mechanism Principle of the SCMG Robot

Generally, the doffing operation includes two steps: doffing cops and donning bobbins, as shown in Fig. 2a. There have been some effective measures to donning bobbins in the spinning industry. This paper concentrates on the methods of doffing cops.

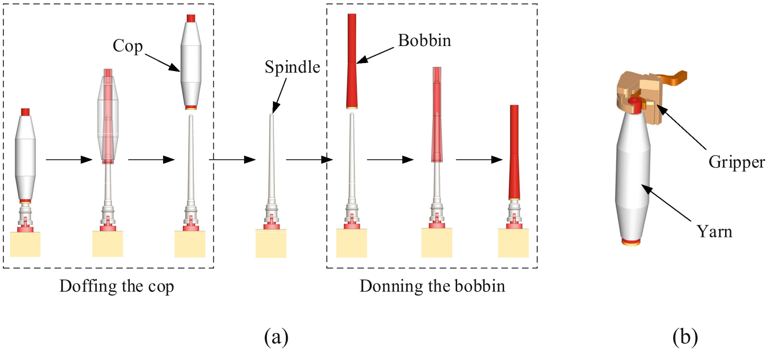


Fig. 2. The doffing operation

Some requirements have to be satisfied during the process of doffing cops:

(a) The relative motion trend in the horizontal direction between the cop and the spindle is not allowed for protecting spindles before the cop leaves the spindle totally;
(b) Grippers cannot touch the yarn, so as not to damage the yarn.

The grippers grasp the top of cops in order to avoid damaging the yarn, because there are no yarns in the top of cops, as shown in Fig. 2b.

The mechanism principle of the SCMG robot is shown in Fig. 3. The grippers are fixed to the sliding blocks. On one hand, the sliding block is sleeved on the vertical rail and can move up or down along the vertical rail. On the other hand, the sliding block is sleeved on the space curve guide rail and has to move along the track of the space curve guide rail. The vertical guide rails are fixed to horizontal conveyors through fixed hinges. The distance (or arc length) between two adjacent vertical guide rails is equal. Therefore, the vertical guide rails can move along with horizontal conveyors. The sliding blocks follow the horizontal movement of vertical guide rails. Meanwhile, the sliding blocks move up or down due to the constraint of the space curve guide rail. Therefore, the grippers achieve the three-dimensional motion.

The horizontal component of the velocity of grippers is equal to the velocity v_1 of horizontal conveyors in the linear segment. When the velocity v_1 of horizontal conveyors is equal to the velocity v_0 of the frame of the SCMG robot, the gripper and the spindle can remain relative static state during the doffing process.

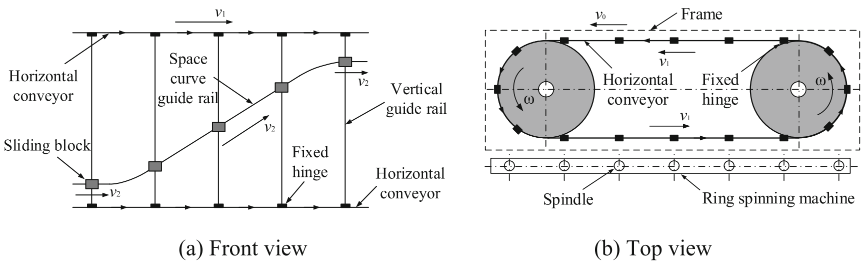


Fig. 3. The mechanism principle of the SCMG robot

2.2 Structure of the SCMG Robot

The structure of the SCMG robot is shown in Fig. 4 shows the SCMG robot mainly consists of a moving device, a locating device, a doffing device, multiple grippers, a bobbin insertion device and a frame. Figure 5 shows the general layout when the SCMG robot works in the ring spinning workshop.

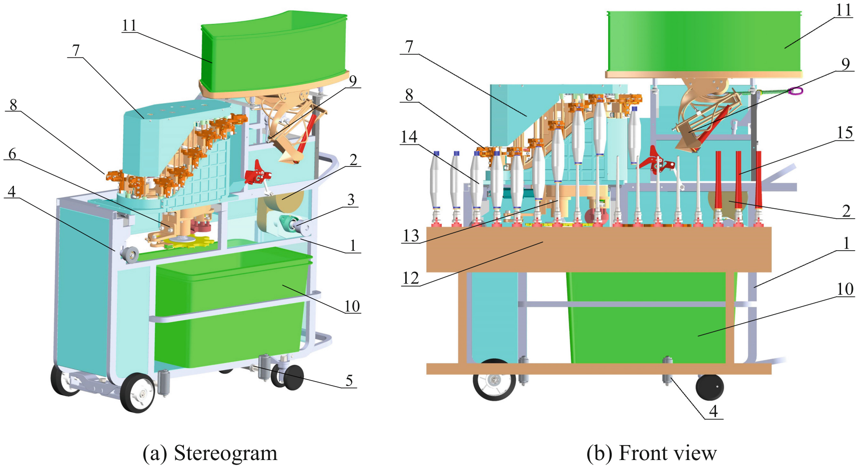


Fig. 4. The structure of the SCMG robot. 1-frame; 2-first motor; 3-active guide roller; 4-following guide roller; 5-support roller; 6-locating device; 7-doffing device; 8-gripper; 9-bobbin insertion device; 10-cop basket; 11-bobbin basket; 12-ring spinning machine; 13-spindle; 14-cop; 15-bobbin.

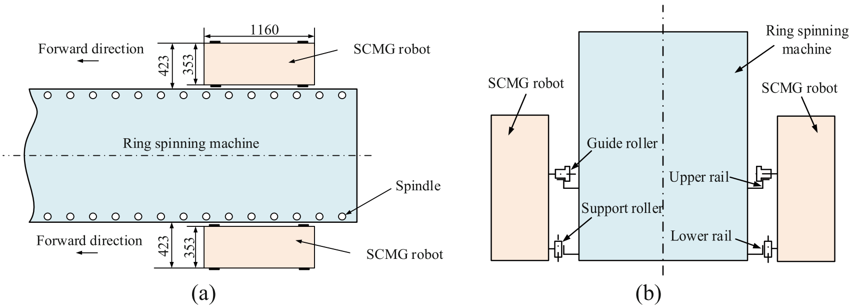


Fig. 5. The general layout when the SCMG robot works in the ring spinning workshop

(1) The Moving Device of the SCMG Robot.

The moving device include the first motor, one active guide roller, one following guide roller, two support rollers and matching connecting shafts. The first motor is placed in the frame and fixed to the shaft of the active guide roller. The two guide rollers and two support rollers mount on the matching shafts respectively, and the matching shafts are set on the frame. The active and following guide rollers contact with the upper rail of the ring spinning machine. The two support rollers contact with the lower rail of the ring spinning machine.

(2) The Locating Device of the SCMG Robot.
The locating device can insure the positional accuracy of the SCMG robot, so that the grippers can grasp cops in a proper position. The locating device is mainly composed of the toothed disc, the locating input shaft, the locating output shaft, the locating transmission mechanism, the first motor and two friction wheels, as shown in Fig. 6. The toothed disc is fixed to the locating input shaft and can mesh with the bottom of spindles of ring spinning machines. The locating input shaft connects with the input terminal of the locating transmission mechanism. The locating transmission mechanism is placed in the bottom of the doffing device and the output terminal of the locating transmission mechanism connects with the locating output shaft. The first friction wheel is fixed to the locating output shaft. The second friction wheel is arranged on the locating transmission mechanism and contacts with the first friction wheel. The output shaft of the second motor is fixed to the second friction wheel.

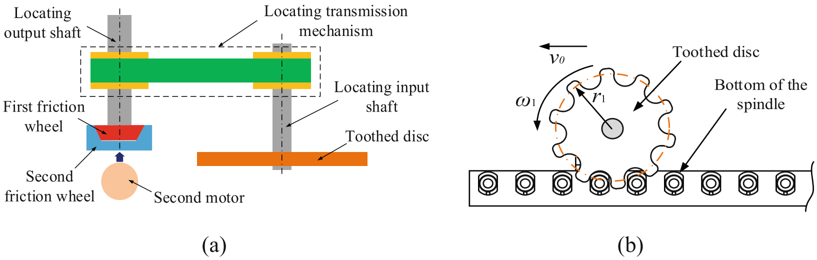


Fig. 6. The mechanism principle of the locating device of the SCMG robot

The function of the second motor is to provide the locating output shaft with extra power, so that the load of the toothed disc can be reduced. The power transmission between the second motor and the locating output shaft is accomplished with the two friction wheels. The transmission ratio between the toothed disc and the locating output shaft is constant, while the transmission ratio between the two friction wheels is not. Hence, it is not necessary to keep the two friction wheels at the same rotating speed. What need to do is to ensure that the rotating speed of the second friction wheel is faster than that of the first friction wheel, so the second motor can provide the locating output shaft with extra power rather than extra resistance.

(3) The Doffing Device of the SCMG Robot.
The doffing device (shown in Fig. 7) mainly consists of the first driving shaft, the second driving shaft, the chains, the first chain wheels, the second chain wheels, the spatial cam, the vertical guide rails, the sliding blocks, the track rollers and the base. The base is mounted on the frame. The spatial cam is fixed to the base. The first and the second cams are fixed to the spatial cam. The first driving shaft is placed in the base and fixed to the locating output shaft. The second driving shaft is placed in the base. The first chain wheels are fixed to the first driving shaft. The second chain wheels are movably sleeved

on the second driving shaft. The chain is set between the first chain wheel and the second chain wheel. The vertical guide rails are fixed to the chain. The distance (or arc length) between two adjacent vertical guide rails is equal to the distance between two adjacent spindles. The sliding blocks are movably sleeved on the vertical guide rails respectively and can slide along the vertical direction. The gripper and the track roller are fixed to the sliding block respectively. The movable claw is placed in the gripper. The track rollers contact with the spatial cam.

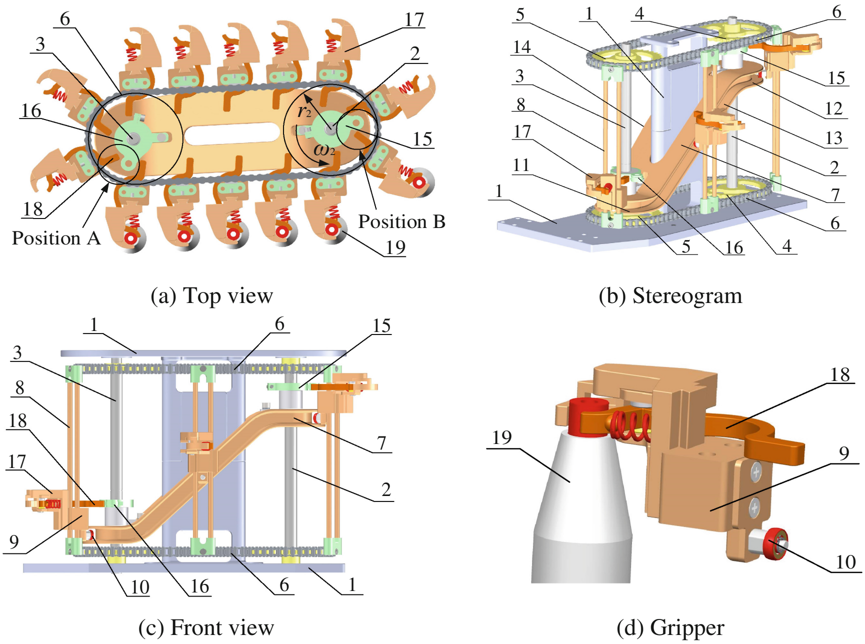


Fig. 7. The doffing device of the SCMG robot. 1-base; 2-first driving shaft; 3-second driving shaft; 4-first chain wheel; 5-second chain wheel; 6-chain; 7-spatial cam; 8-vertical guide rail; 9-sliding block; 10-track roller; 11-lower horizontal segment of the spatial cam; 12-upper horizontal segment of the spatial cam; 13-upslope segment of the spatial cam; 14-downhill segment of the spatial cam; 15-first cam; 16-second cam; 17-gripper; 18-movable claw; 19-cop.

When the doffing device works, the grippers will move along the track of the spatial cam. Generally, the path of the spatial cam can be divided into four parts, i.e., the lower horizontal segment, the upper horizontal segment, the upslope segment and the downhill segment, as shown in Fig. 7b and c. Moreover, there are circular arc transition between two adjacent segments.

3 Doffing Process of the SCMG Robot

This section introduces the doffing process of the SCMG robot in detail.

The first motor starts and drives the active guide roller to rotate. So the frame moves forward on the upper rail of the ring spinning machine. The toothed disc is pulled by spindles and starts to rotate. The toothed disc drives the first driving shaft and the first chain wheels to rotate via the locating transmission mechanism. Then the vertical guide rails move along with the rotational motion of the chain. The sliding blocks follow the horizontal movement of the vertical guide rails, on the other hand, the sliding blocks move up or down due to the constraint of the spatial cam. Therefore, the grippers achieve the three-dimensional motion.

As shown in Fig. 8, v_0 is the velocity of the frame, v_1 is the velocity of grippers. In order to ensure that grippers can pull the cops out of the spindle vertically, the horizontal component of the velocity of grippers should be equal to the velocity of the frame identically.

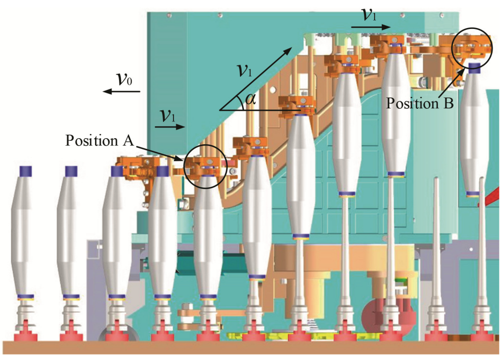


Fig. 8. The doffing process of the SCMG robot

Analyzing Figs. 6, 7 and 8, one obtains:

$$\omega_1 r_1 = v_0 \tag{1}$$

$$\omega_2 r_2 = v_0 \tag{2}$$

Combining the Eqs. (1–2), one gets:

$$i = \frac{\omega_1}{\omega_2} = \frac{r_2}{r_1} \tag{3}$$

There, i is the transmission ratio of the locating transmission mechanism, r_1 is the pitch diameter of the toothed disc, r_2 is the pitch diameter of the first driving wheel.

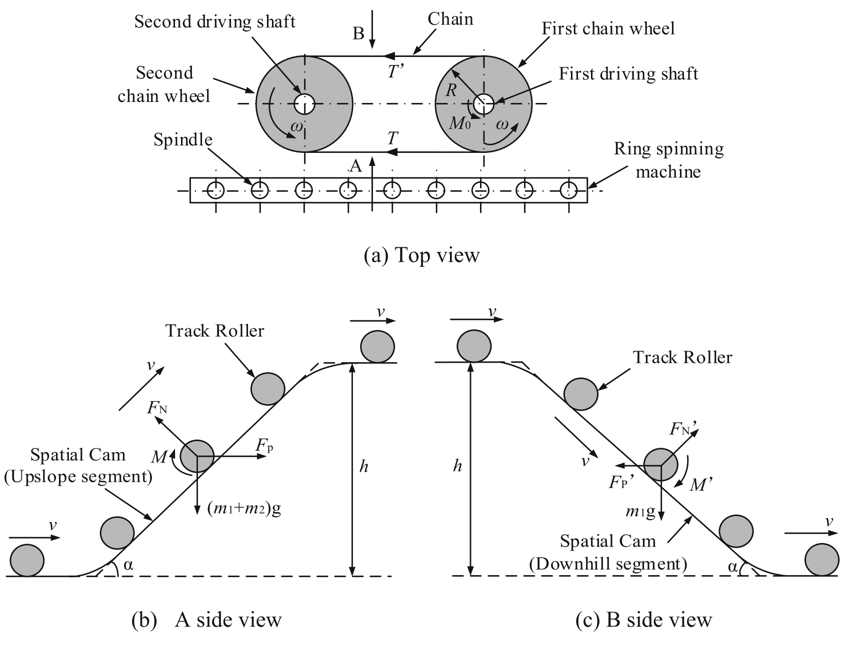
When the transmission ratio of the locating transmission mechanism satisfies the Eq. (3), grippers and spindles can remain relative static state during the doffing process.

As shown in Figs. 7 and 8, when a gripper reaches position A, the movable claw of the gripper is pushed by the second cam. Then the gripper opens and grasps the top of a cop. After that, the gripper moves into the upslope segment of the spatial cam.

The gripper rises up with the cop together. When the gripper moves into the upper horizontal segment of the spatial cam, the cop leaves the spindle totally. The gripper keeps moving forward. The movable claw is pushed by the first cam in position B, the gripper opens again and releases the cop. The cop basket collects the cop. The gripper continues to move along the path of the spatial cam until it reaches the position A again, and then the gripper begins the next doffing cycle. During the whole doffing process, the gripper neither contacts the yarn nor damages spindles.

4 Force Analysis of the Doffing Process

The doffing device is a critical subsystem of the SCMG robot, which has a great effect on the operation efficiency and the doffing result of the SCMG robot. Therefore, it is essential to analyze the force imposed on the doffing device. The force analysis of the doffing device is shown in Fig. 9. When the track roller is at the horizontal segment of the spatial cam, the rolling friction force between the track roller and the spatial cam is too small to influence the operational efficiency and can be neglected. Moreover, the friction between the gripper and the vertical guide rail is neglected. The mass of a gripper is assumed to converge at the center of the track roller in order to simplify the analysis model.



(a) Top view

(b) A side view

(c) B side view

Fig. 9. Force analysis of the doffing device of the SCMG robot

Let: m_1- the total mass of a gripper, a sliding block and a track roller, kg;

m_2 - the mass of a cop, kg;

F_N - the support force to track roller imposed by spatial cam, N;

R - the radius of the track roller, mm;
M - the rolling friction torque to track roller imposed by the spatial cam, Nm;
F_P - the tractive force to the gripper imposed by the chain, N;
v - the velocity of the gripper, $\mathrm{m} \cdot s^{-1}$;
T - the tensile force of the chain, N;
M_0 - the actuated moment of the first driving shaft, Nm;
R - the radius of the first chain wheel, mm
l_0 - the distance between two adjacent spindles, mm;
h - the vertical height of the upslope (or downhill) segment of the spatial cam, mm;
μ_1 - the coefficient of rolling friction between the spatial cam and track rollers, mm;
α - the angle between the upslope (or downhill) segment of the spatial cam and the horizontal plane, (˚).

According to the force analysis, the rolling friction torque imposing on the track rollers is as follows:

$$\begin{pmatrix} M \\ M' \end{pmatrix} = \begin{pmatrix} \mu_1 F_{\mathrm{N}} \\ \mu_1 F'_{\mathrm{N}} \end{pmatrix} \tag{4}$$

As shown in Fig. 7b, according to the force balance of the track roller in the upslope segment of the spatial cam, one obtains:

$$\begin{pmatrix} F_{\mathrm{P}} & F_{\mathrm{N}} & 1 \end{pmatrix} = \begin{pmatrix} \frac{M}{r}\sin\alpha & \frac{M}{r}\cos\alpha & 1 \end{pmatrix} \begin{pmatrix} r/\mu_1 & -1/\cos\alpha & 0 \\ -1 & 0 & 0 \\ 0 & (m_1 + m_2)g/\cos\alpha & 1 \end{pmatrix} \tag{5}$$

Likewise, according to the force balance of the track roller in the downhill segment of the spatial cam, as shown in in Fig. 7c, one obtains:

$$\begin{pmatrix} F'_{\mathrm{P}} & F'_{\mathrm{N}} & 1 \end{pmatrix} = \begin{pmatrix} \frac{M'}{r}\cos\alpha & \frac{M'}{\mu_1}\sin\alpha & 1 \end{pmatrix} \begin{pmatrix} -1 & 0 & 0 \\ 1 & \frac{-\mu_1}{r\cos\alpha} & 0 \\ 0 & \frac{m_1 g}{\cos\alpha} & 1 \end{pmatrix} \tag{6}$$

Combining Eqs. (4–6), the following relationship is arrived at:

$$\begin{pmatrix} F'_{\mathrm{P}} & F_P & 1 \end{pmatrix} = \begin{pmatrix} \frac{m_1 g}{r + \mu_1 \tan\alpha} & \frac{(m_1 + m_2)g}{r - \mu_1 \tan\alpha} & 1 \end{pmatrix} \begin{pmatrix} r\tan\alpha - \mu_1 & 0 & 0 \\ 0 & r\tan\alpha + \mu_1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{7}$$

In order to calculate the actuated moment M_0 of the first driving shaft, it is necessary to figure out the maximum number of the track rollers locating on the upslope and downhill segment of the spatial cam. When setting the maximum number as n, one gets:

$$n = \left\lceil \frac{h}{l_0 \tan\alpha} \right\rceil, (\lceil x \rceil = \min\{k \in Z | x \le k\}) \tag{8}$$

The cop has to rise 180 mm at least when leaving the spindle totally, i.e., the vertical height of the upslope (or downhill) segment of the spatial cam has to be greater than or equal to 180 mm. Here assume $h = 200$ mm and $l_0 = 70$ mm. Considering the compactness of the doffing device, one assumes $2 \le n \le 6$, so the value range of the angle α is:

$$25.5^\circ \le \alpha \le 70.7^\circ \tag{9}$$

$$T = nF_P \tag{10}$$

$$T' = nF'_P \tag{11}$$

$$\begin{pmatrix} M_0 & 1 \end{pmatrix} = \begin{pmatrix} R & R \end{pmatrix} \begin{pmatrix} T & 0 \\ -T' & 1/R \end{pmatrix} \tag{12}$$

Combining Eqs. (7–12), the following relationship is arrived at:

$$M_0 = gR \left\lceil \frac{h}{l_0 \tan\alpha} \right\rceil \left[\frac{r\tan\alpha + \mu_1}{r - \mu_1 \tan\alpha}(m_1 + m_2) - \frac{r\tan\alpha - \mu_1}{r + \mu_1 \tan\alpha} m_1 \right] \tag{13}$$

Considering the compactness of the spatial cam, the value range of the radius of the track roller has to be limited in [4 mm, 12 mm], i.e., $r \in [4\,\text{mm}, 12\,\text{mm}]$.

In order to figure out the relationship among the actuated moment M_0, the angle α and the radius r of the track roller, setting some variables' value in Eq. (13) is necessary. Assume $m_1 = 1\,\text{kg}$, $m_2 = 0.5\,\text{kg}$, $R = 66\,\text{mm}$, $\mu_1 = 0.05\,\text{mm}$, $g = 9.8\,\text{m} \cdot \text{s}^{-2}$. So the relationship among the actuated moment M_0, the angle α and the radius r of the track roller can be described as Fig. 10.

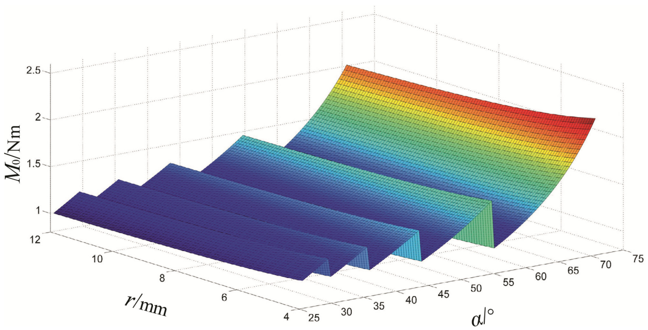


Fig. 10. The relationship among the moment M_0, the angle α and the radius r.

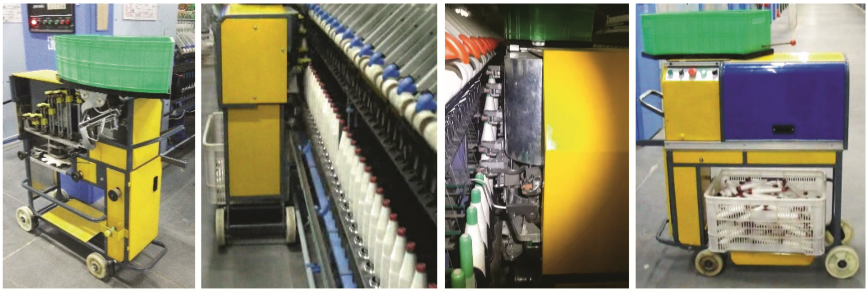
Figure 10 shows that the relationship between the actuated moment M_0 and the angle α is similar to the piecewise function. When $M_0 = M_{0,\min}$, the angle α can be several possible value within the limited range, as follows:

$$\alpha = \{25.5^\circ, 29.9^\circ, 35.9^\circ, 43.9^\circ, 55.1^\circ\} \tag{14}$$

The designers can choose one of the values according to the demand of the configuration. In addition, there is a negative correlation between the radius r of the track roller and the actuated moment M_0 of the first driving shaft. Therefore, the designers should choose the track roller with the larger radius in the admitted range.

5 Doffing Experiments of the SCMG Robot

Figure 11 shows the doffing applications (experiments) of the SCMG robot. The SCMG robot has been applied to the ring spinning factory for the purpose of evaluating the performances. The key performances of manual doffing, the SCMG robot and double-disc doffer are shown in Table 1.



(a) (b) (c) (d)

Fig. 11. The doffing applications of the SCMG robot

Table 1. The key performances of several typical doffing robot [1, 10]

Indicators	Manual doffing	Double-disc doffer	SCMG robot
Doffing rate	100 %	96 %	99 %
Doffing time (240 spindles)	about 150 s	about 50 s	60 s
Damage yarns or not?	No	Yes	No
Damage spindles or not?	No	Yes	No

The Table 1 shows that the doffing efficiency of the SCMG robot is close to that of double-disc doffer and much higher than that of manual doffing. Different from the double-disc doffer, the SCMG robot does not damage spindles and yarns in the doffing process.

6 Conclusion

This paper developed a novel continuous single-spindle doffing robot with a spatial cam and multiple grippers for ring spinning machines, called the SCMG robot. The SCMG robot mainly consists of a doffing device, a moving and locating device. The doffing device is composed of 14 grippers moving along a fixed 3D trajectory of a spatial cam. The moving and locating device adopts a positioning wheel meshing with the bottom of spindles. Experimental results show that the SCMG robot can pull the cops out of the spindle vertically one by one. The grippers grasp the top of the cops without touching yarns. The SCMG robot is highly efficient and reliable.

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References

1. Gao, X.: Function study of a new auto-doffing spinning frame. China Textile Leader (01) (2011)
2. Watanabe, E.: Toyoda continuous auto-doffer. J. Textile Mach. Soc. Japan **11**, 213–216 (1965)
3. Inoo, O.: Pony doffer: an automatic doffing apparatus for single-spindle, continuous doffing system. J. Textile Mach. Soc. Japan **11**, 223–236 (1965)
4. Hori, J., Kinari, T., Shintaku, S.: Development of an auto-doffer for covering machine part 1: apparatus for drawing spandex into hollow spindles. J. Textile Mach. Soc. Japan **44**(4), 82–86 (1998)
5. Han, W.: On the understanding of smart doffing trolley. Sci. Technol. Innovation **08**, 42–43 (2014)
6. Cao, M.: Introduction of the abroad novel automatic doffer. Shanghai Text. Sci. Technol. **53**(2), 60–61 (1991)
7. Zheng, K.: Discussion about developing automatic doffer for the spinning system. Text. Mach. (04) (2010)
8. Wang, H., Fei, H.: Design and analysis of two-way clutch for spinning automatic doffers. Shandong Text. Sci. Technol. **28**(2), 13–15 (2000)
9. Ruan, Y., Suo, S., Jia, J., et al.: The mechanical analysis of the doffing process and the mechanical design of the robot doffer in the ring spinning process. Text. Accessories **40**(4), 1–5 (2013)
10. Li, S., Zhang, Y.: S12 intelligent doffer produces considerable economic benefit. China Textile News, 2015-10-26, 007 (2015)