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Study on the roller array based package transport and sorting platform

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The automatic conveying line is the key equipment of material flow system in logistics distribution centers. However, conventional automatic conveying line would take up a relatively large place, yet it could only perform simple tasks such as moving packages along a straight line. It is also difficult and costly to add/change an existing conveying line, which makes the distribution center rigid, inflexible, and unfriendly to maintain. To improve the automatic conveying line, this paper proposed a roller array-based package transport and sorting platform, which can be used for logistics distribution centers for advanced automatic conveying purposes. The roller unit is the key component of the platform. It consists of a swiveling roller and a swiveling motor which give the packages the required direction and velocity. Package detection technique is also integrated in the platform to detect the geometry center of the moving package for transport feedback control. The proposed control algorithm enables the platform to perform package translation, rotation, turning and a normal transport. The experiment results show that the transport velocity error is about 6% and the rotation angular velocity error is 5%. The package could move along the designed 'S' shape trajectory. The proposed roller array-based package transport and sorting platform could control the package movement as required.

1. Introduction

The logistics distribution center plays a critical role in the overall logistics industry, it could receive, sort, transport and distribute incoming packages across different regions efficiently [1].

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At present, the automatic conveying line is the key to improving the efficiency of the logistics distribution center. The automatic conveying line can be classified as a roller sorter, slider sorter and cross belt sorter [2, 3]. The automatic conveying line has several drawbacks. Firstly, it can only perform simple transport or sorting tasks. Secondly, for each logistics distribution center, the whole automatic conveying line must be carefully planned; it is very difficult and costly to modify the existing conveying line. Moreover, the failure rate as well as the maintenance costs of automatic conveying line should be carefully considered, since even one failure in a part of conveying line might stop the whole package distribution process. Recently, engineers and researchers have paid lots of effort to develop a robust and intelligent package transport and sorting equipment aimed to improve the package distribution efficiency, reduce the distribution error rate and production costs.

Overmeyer et al. [4] proposed small-scaled modules for intralogistics operations. Four swiveling roller were arranged in a row and driven by a swivel mechanism, where a self-aligning coupling part would swivel four swiveling roller at the same time. The swiveling roller could also rotate around its own axis to deliver the package forward and backward. This system was designed to transport and sort packages. The specially designed swiveling rollers and relevant driven system helps reducing the investment costs and substantially facilitates the realization of package transport. However, the swiveling function of four swiveling rollers was based on a single servo motor. The four swiveling rollers must swivel in the same direction, therefore reducing the flexibility of this system.

Seibold [5] proposed swiveling modules for package transport. Instead of utilizing one shaft to drive four swiveling rollers in a row, one driven motor was designed for each swiveling roller. Multiple swiveling rollers with integrated drive were utilized to create a functional intralogistics node which could perform tasks such as transporting, collecting, separating, sorting, merging, sequencing and aligning the packages. For this system, a decentralized controlled system has been also developed. Each swiveling rollers unit has its own controller, which can communicate with a nearby swiveling rollers unit, therefore avoiding package collision during the package transport process. However, the package transport trajectory was planned and analyzed based on simulation experiments and the detailed working strategies of each swiveling module were not discussed.

Uriarte [6] and Sun [7] both proposed a new kind of small-scaled conveyor systems, which utilized the cellular conveyor unit as the modular conveyor and positioning system. The cellular conveyor mainly consisted of three omnidirectional wheels, which worked together to transport packages. The feedback system consisted of an RGB-D camera, which delivered a 2D image and a 3D point cloud. The tracking error was ±5 cm and the velocity error was ±0.02 m/s. However, the working principle of omnidirectional wheels causes that package delivery would induce extra friction force, which affects its service life.

In recent years, due to the rapid development of outer rotor motors [8–10] and their drive system, it is more likely to utilize the affordable outer rotor motor as the swiveling roller. Therefore, the swiveling roller would be able to rotate by itself instead of using complex driving mechanisms such as shaft or belt. With an extra motor to rotate the swiveling roller's holding piece, the swiveling roller would be able to swivel in the required direction. The modularization design of a roller unit consisting of two motors would make the automatic conveying line more flexible. Besides, detection technology is also rapidly developing recently, meanwhile the price of detection sensor keeps decreasing. The photoelectric sensor [11–13] is a suitable choice for the roller unit to detect package position and posture in real time, which would provide package information for an automatic conveying line to make intelligent decision for package transport and sorting. The roller unit with detection ability would help building modular, flexible and intelligent automatic conveying line, which would improve package transport and sorting process.

This paper proposes a new roller array-based package transport and sorting platform as well as its control algorithm. The proposed platform could be used as an automatic conveying line. Each roller unit consists of a detection part and an actuation part. The detection part would help to detect the position and posture of the package, while the actuation part would help to move the package. The cooperation of multiple roller units would help the packages to translate or rotate along planned trajectory. In the following sections, the working principle of the roller unit as well as the control algorithm for package transport and sorting would be introduced. The experiment results will also be shown and analyzed.

2. The features of roller array based transport platform

To reduce costs and improve efficiency during the package transport process, in this article we propose a new modular, flexible and intelligent roller array based package transport and sorting platform. Meanwhile, the related package transport and sorting control algorithm is also studied.

The schematic diagram of package transport and sorting platform is shown in Fig. 1. Multiple roller units would detect the package position and posture, meanwhile these roller units would cooperate with each other to transport and sort a package. This platform system has the following features:

1. Modularization: The main components of the transport platform are based on the modularized roller unit. A single roller module is the minimum functional unit of the platform system. Several roller units can be assembled as a roller array, which can be used for package transport and sorting. The overall size and shape of the platform can be determined by its working conditions. A single failed roller unit would not stop the whole conveyor system, so it is much easier to fix the problem by replacing the failed roller unit. This modularized design can help reducing the equipment costs, as well as operation and maintenance costs.

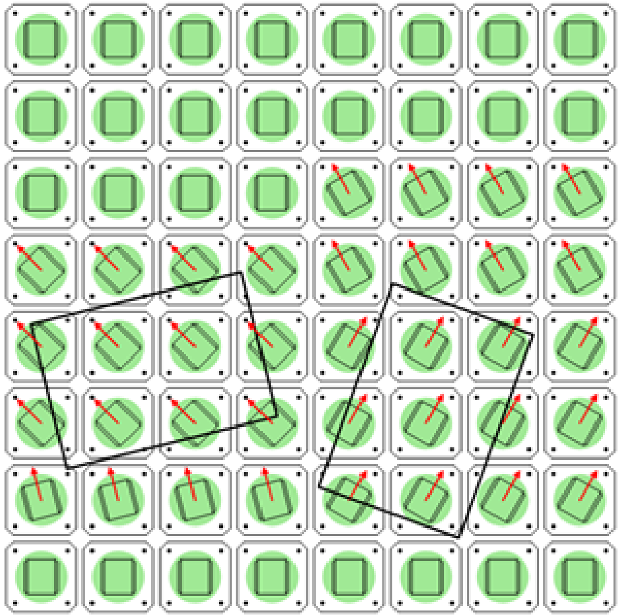


Fig. 1. Schematic of package transport and sorting platform

2. Flexibility: Each single roller unit is equipped with a separate outer rotor motor as the roller for rotation and a drive motor for swiveling. Both motors are driven by a local controller. With the two motors and the local controller, the roller unit can realize omni-directional and multi-stage transport, thus transport the package to any direction at a required speed. In addition, multiple roller units can cooperate with each other to complete basic actions such as package translation, package rotation and the combination of these two. Multiple roller units can be used for package transporting, collecting, separating, sorting, merging, sequencing and aligning during the package distribution process.
3. Intellectualization: Four photoelectric sensors are placed in each roller unit's four corners. Multiple sensors from the roller unit array can form a sensor array. Firstly, the detected information are collected by the local controller of roller unit, then are sent to the main controller of the platform. Therefore, the main controller can monitor the position and posture of packages in real-time. Besides, the main controller can also monitor the status of each roller unit through protocol communication. Based on the actual position and posture of the package, as well as the roller unit's status in real time, the main controller can apply the package transport control algorithm to complete the package transport and sorting operation.

Based on the normal package transport and sorting condition, the required working parameters of a roller unit are shown in Table 1.

Table 1. Working parameters

Working parameters of roller unit		
Parameters	Values	Unit
Rolling velocity	0.3–2.0	m/s
Swiveling range	0–360	°
Swiveling angular velocity	2π–4π	rad/s
Loading capacity	5	kg
Working parameters of platform		
Transport velocity	0.3–2.0	m/s
Package rotation angle	0–360	°
Rotation angular velocity	1	rad/s
Package weight	< 20	kg

3. Roller unit

The roller unit (Fig. 2) is the basic component of the roller-array-based package transport and sorting platform. Each unit consists of a detection part, an actuation part and a local controller. When the platform is working, the local controller will periodically command the detection part to monitor the package status and send the detection information to the main controller. After the main controller calculates the package's position and posture, as well as the planned trajectory, the main controller will send new commands to every roller unit. Then, the local controller of each roller unit will follow the new command to control the swiveling angle and rotation speed of the roller. Multiple roller units would then work together to move the package along the planned trajectory with a specified posture and at a desired speed.

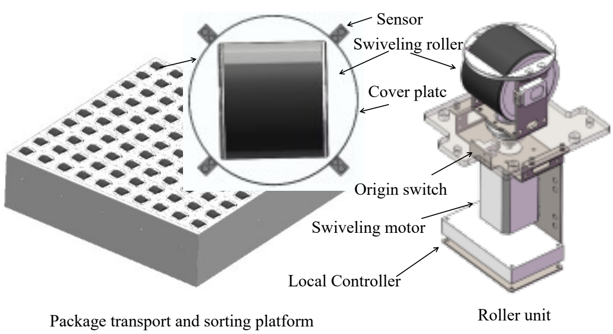


Fig. 2. Platform and roller unit

3.1. Detection part

The main component of the detection part is a photoelectric sensor, which contains an infrared transmitting tube and a receiving tube. With the photoelectric sensor, the detection part can detect the appearance and disappearance of the moving package within 30 mm above it. Compared with the vision system with a camera [14, 15], the photoelectric detection part will neither be affected by package material, package color, surface curvature, residual sticker, nor by the environmental light source [16, 17]. Each roller unit consists of four photoelectric sensors at four corners. The four sensors are placed lower than the rolling motor cover plate. When the package moves above the roller unit, the detection part will be triggered in real time and send a signal to the local controller to help confirm the package's position and posture.

3.2. Actuation part

The actuation part is proposed to help transport the packages at the required speed and direction. For each roller unit, two individual motors are necessary for rolling and swiveling movements.

An outer rotor motor is selected as the swiveling roller, which rotates at the required speed. The friction force between the roller and the packages helps move the packages, therefore the power of the outer rotor motor can be calculated as:

$$P = \frac{fv}{\eta} = \frac{\mu mgv}{\eta}, \tag{1}$$

where P is the power of the outer rotor motor, f is the friction force between the roller and the package, v is maximum transport velocity of packages, η is the power transfer efficiency, μ is the friction coefficient, m is the loading weight applied on a single roller unit.

Besides, the nominal torque of outer rotor motor T_H can be expressed as:

$$T_H = fr = \mu mgr, \tag{2}$$

where r is the radius of outer rotor motor.

Then, the rotation speed n can be expressed as:

$$n = \frac{60v}{2\pi r}. \tag{3}$$

The outer diameter of the roller is set to 60 mm, to suit the package size and the swiveling motor's power. Assuming that a single actuation part bears 5 kg weight of a stationary package and the maximum transport velocity of a package is set to 2 m/s, the transfer efficiency is 97% and the friction coefficient is 0.5, after calculation based on equations (1)–(3), the power of roller should be larger than 51 W, the nominal torque should be larger than 0.73 Nm and the rotation speed should be larger than 537 rpm.

To meet the above requirements, one type of specially designed outer rotor motor is selected as the roller. This outer rotor motor utilizes a Hall sensor to control the rotation speed, and it has rubber outer surface to supply friction force.

The swiveling motor is used to change and maintain the roller's direction. During the transport process, the swiveling motor must overcome the friction force from the packages. The package presses the roller unit and induces an extra friction force. However, the supporting component utilizes a ball bearing to carry the weight of the package, therefore the extra friction force can be ignored.

The nominal toque of the swiveling motor T_S can be calculated as:

$$T_S = 2 \int\limits_0^{L/2} \mu M g r \, \mathrm{d}r, \tag{4}$$

where the L is the width of a roller motor and M is the loading weight on a roller unit. Assuming that the whole package is supported by one roller unit, L is 0.07 m and M is 20 kg, the nominal toque should be larger than 0.12 Nm.

To meet the above requirements, the stepping motor is selected.

Based on the selected motors for rolling and swiveling purposes, the basic structure of the actuation part can be determined (Fig. 1).

When the swiveling roller rotates, the friction force between the outer rubber surface and the package will help moving the package, therefore realizing the movement of package. The swiveling roller is fixed on a supporting piece with a ball bearing. When receiving a command from the local controller of the roller unit, the swiveling motor will swivel roller to a specified angle to change the direction of friction force applied to the package, therefore changing the package's movement direction. Besides, the origin switch would be used for recalibration to ensure that the initial postures of roller units are consistent when the actuation part operates for a relatively long time. By utilizing swiveling roller and swiveling motor together, one makes that the roller unit will rotate towards the specified direction at the required speed to apply the friction force to the packages.

3.3. Local controller

The local controller of roller unit controls the roller's and swiveling motor's working status. The local controller is also a slave controller, which communicates with the master controller (main controller) of the transport platform system through the CAN bus. The brushless roller motor is usually driven with a closed-loop PI control method [18, 19]. In this paper, a speed-current double closed-loop PI control method was selected. This control method can 1) make the roller motor start with maximum current to improve the response speed; 2) quickly recover its stability with a suddenly changing load; and 3) closely follow the given speed therefore reducing speed fluctuation. The control method can improve the roller's performance. The swiveling motor is controlled by the PWM pulse wave. It can realize the trapezoidal acceleration and deceleration control of the swiveling motor for swiveling purposes.

In addition, the main controller, which is also the master controller of the transport platform system, communicates with the warehouse management system (WMS) through the Ethernet communication. The WMS will send information about each package including the package sequence and destination. The main controller monitors the relevant package's position and posture, then it plans the package's transport trajectory.

4. Package detection

During the package transport process, the transport platform detects the size, position and posture of a moving package, calculates the required rotation speed and swiveling angle for each roller unit, and sends commands to all the roller units. Then, the roller and the swiveling motor work together to transport the package along the correct trajectory. The movement of packages is monitored to provide feedback information, therefore, the control algorithm is able to correct the package transport velocity and direction in real time. By utilizing the feedback information and update the commands for roller units, the proposed transport platform will enable the package to move at required speed and direction.

4.1. Coordinate system and parameter definition

Assuming the transport platform has a world coordinate system XOY (Fig. 3), the lower left corner of the platform is taken as the origin of the coordinate system, and the center (x_i, y_j) of each of the roller units is defined based on their real position values, where i and j are the indices for each roller unit.

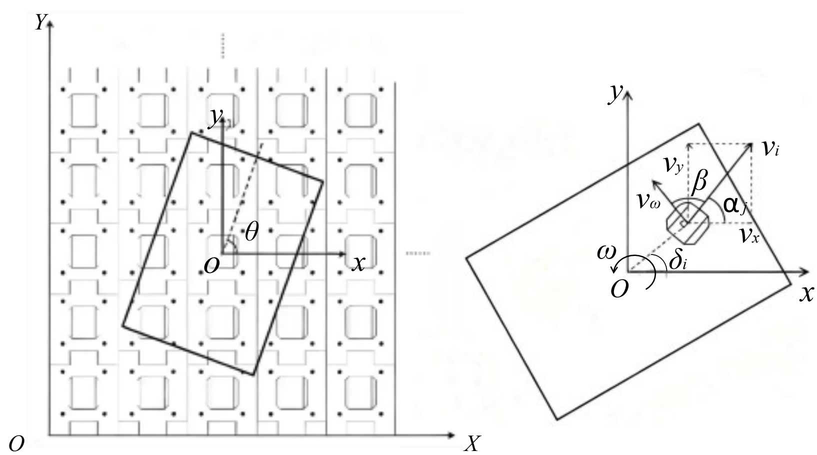


Fig. 3. Package in world coordinate system XOY

Then, a matrix could be used to express the all the roller units' center positions:

$$D_g = \begin{bmatrix} (x_1, y_1) & & \dots & & (x_1, y_n) \\ & \ddots & & & \\ \vdots & & (x_i, y_j) & & \vdots \\ & & & \ddots & \\ (x_m, y_1) & & \dots & & (x_m, y_n) \end{bmatrix}_{\substack{i=1,\dots,m \\ j=1,\dots,n}} . \tag{5}$$

For the four photoelectric sensors mounted on the each roller unit corners, the relevant coordination can be expressed as:

$$S_{ij-k} = \begin{bmatrix} S_{ij-1} & S_{ij-2} \\ S_{ij-3} & S_{ij-4} \end{bmatrix} = \begin{bmatrix} x_i - b,\ y_j + c & x_i + b,\ y_j + c \\ x_i - b,\ y_j - c & x_i + b,\ y_j - c \end{bmatrix}, \tag{6}$$

where b and c are the half of distances between two adjacent photoelectric sensors along X and Y axis, respectively.

Besides, the local coordinate system xoy (Fig. 3) is defined for each moving package, where x and y axes are parallel to the X and Y axes of the world coordinate system, and the origin coincides with the package geometry center. The movement of local coordinates along X and Y axes can be used to express the relative translation between the package center and the platform origin. Therefore, the package transport velocity can be expressed by the relative velocity between coordinate systems xoy and XOY. Meanwhile, the rotation of package is defined by the package rotation angle θ between the package centerline and x axis of the local coordinate (Fig. 3).

4.2. Package detection method

Assuming a package has a rectangular shape, the photoelectric sensors on the surface of platform could form a sensor array, which can be used to detect the package position and posture in real time. Based on the sensor array and the detection results, the matrix can be used to determine the position of the package (Fig. 4). It is noted that the distances between adjacent sensors are different. The distance between sensors is 67.2 mm inside each roller unit, and 52.5 mm between two adjacent unit.

Among all the sensors that have detected the package, there are four marked sensors with the largest x axis value $(x_{\max}, y)$, the smallest x axis value $(x_{\min}, y)$, the largest y axis value $(x, y_{\max})$ and the smallest y axis value $(x, y_{\min})$. The average value of these four sensors determines the coordinate value of the package center:

$$x_P = \frac{1}{4}\sum_{i=1}^{4} x_i\,, \qquad y_P = \frac{1}{4}\sum_{j=1}^{4} y_j\,. \tag{7}$$

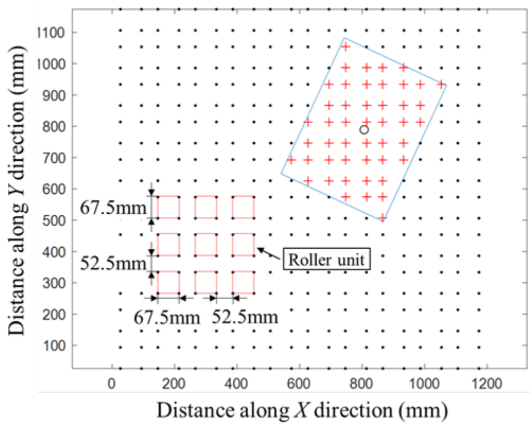


Fig. 4. Sensor array for package detection

Besides, the package rotation angle (Fig. 3) can be expressed as:

$$\theta = \arctan \frac{y_{j_2} - y_{j_1}}{x_{i_2} - x_{i_1}} . \tag{8}$$

Then, it is possible to get the matrix that contains the coordinate values of the package center $(x_\mathrm{P}, y_\mathrm{P})$ and the package angle δ, which can be expressed as:

$$P = \begin{bmatrix} x_\mathrm{P} & y_\mathrm{P} & \theta \end{bmatrix}^\mathrm{T} . \tag{9}$$

It is noted that the coordinate values of package center and package angle are approximate values. However, the control algorithm would periodically detect the package and update the matrix for calculation. When the detection cycle time is sufficiently short and the sensors are arranged closely enough, the control accuracy could be acceptable.

5. Package transport control

After package detection, the transport platform utilizes the roller unit to move the package along the planned trajectory. All the roller units carrying packages execute their own commands, then cooperate with each other and transport the packages. The package movement can be described by the package transport velocity v_P and the transport angle λ. Meanwhile, the state of each involved roller unit can be described by the rolling velocity v_i and the swiveling angle α_i.

Before analyzing the transport control algorithm, three assumptions should be considered: 1) the friction force is large enough so that no slip happens between packages and rollers; 2) the package is assumed as a rigid body and has no deformation; 3) the friction force starts from the contacting point between the package and the roller, where the contacting point is right above the center of roller unit.

If the geometry center of the package is defined as the base point of rigid body motion, the movement of every point of the package can be expressed as a combination of translation in world coordinates system and rotation around its base point. The movement of package can be expressed as the matrix:

$$Q = \begin{bmatrix} v_{\mathrm{P}x} & v_{\mathrm{P}y} & \omega_{\mathrm{P}} \end{bmatrix}^{\mathrm{T}}, \tag{10}$$

where $v_{\mathrm{P}x}$ and $v_{\mathrm{P}y}$ are the package translation velocities in world coordinates system along X axis and Y axis respectively; the combination of vectors $v_{\mathrm{P}x}$ and $v_{\mathrm{P}y}$ can be used to express the package transport velocity $v_{\mathrm{P}}\angle\lambda = v_{\mathrm{P}x} + v_{\mathrm{P}y}$, where λ is the transport angle; ω_{P} is the package rotation angular velocity around the base point.

Assuming that the touching points between the package and all the relevant roller's surfaces are regarded as points of a rigid body, the roller would have the same velocity and direction at the touching point from rigid body. Considering the roller unit will provide a "rigid body motion" with the package, each relevant roller unit with index i should have the specific rolling velocity, which equals to:

$$\vec{v}_i = \vec{v}_{\mathrm{P}} + \vec{\omega}_{\mathrm{P}} \times \vec{r}_i\,, \tag{11}$$

where r_i is the distance between the relevant roller unit center and the package base point. The rolling velocity v_i is determined by the roller's rotation speed and roller's diameter.

For each relevant roller unit, the rolling velocity in world coordinates system can be expressed as:

$$\begin{aligned} v_i &= v_{\mathrm{P}x}\cos\alpha_i + v_{\mathrm{P}y}\sin\alpha_i + \omega_{\mathrm{P}} r_i\,, \\ r_i &= \sqrt{(x_{\mathrm{P}} - x_i)^2 + (y_{\mathrm{P}} - y_j)^2}\,, \end{aligned} \tag{12}$$

where α_i is the swiveling angle of roller unit i (Fig. 3).

Then, for all the relevant roller units, the matrix of rolling velocity can be expressed as:

$$\begin{bmatrix} v_1 \\ v_2 \\ \vdots \\ v_n \end{bmatrix} = \begin{bmatrix} \cos\alpha_1 & \sin\alpha_1 & r_1 \\ \cos\alpha_2 & \sin\alpha_2 & r_2 \\ \vdots & \vdots & \vdots \\ \cos\alpha_n & \sin\alpha_n & r_n \end{bmatrix} \begin{bmatrix} v_{\mathrm{P}x} \\ v_{\mathrm{P}y} \\ \omega_{\mathrm{P}} \end{bmatrix}. \tag{13}$$

If the package's position and posture are detected by the detection part and the transport trajectory is determined by the platform system, then one can determine the value of transport velocity v_{P}, transport angle λ, package rotation angular velocity ω_{P}, package center $(x_{\mathrm{P}}, y_{\mathrm{P}})$ and the roller unit center (x_i, y_i).

From equation (12) and the known parameter values mentioned above, it follows that the value of swiveling angle α_i should also be determined to realize the package movement.

The swiveling angle α_i is related to the package transport status. By applying different swiveling angles to relevant roller units, the package can be given different movement styles (Fig. 5): a) if all the relevant roller units have the same swiveling angle value and rolling velocity, the package performs translation movement; b) if the roller unit at two sides of the package center have the same swiveling angle value but different rolling velocities, the package performs turning movement; c) if the roller units around the package center have the same rolling velocity but all the swiveling directions are perpendicular to the distance r_i, the package performs rotation movement.

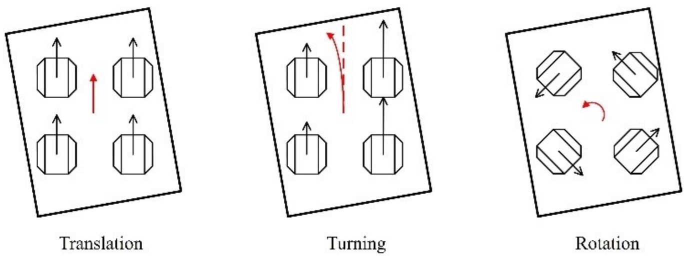


Fig. 5. Package movement styles

Therefore, to control the package transport status, it is necessary to plan first the trajectory of the package, then utilize the swiveling angle α_i to realize such a movement. It is noted that the rolling velocity v_i and swiveling angle α_i are the control parameters of the roller and the swiveling motor, so these two parameters must be determined to control the roller unit.

5.1. Package transport

The movement of package can be classified as translation, rotation, and combination of both two. More complicated movements can be realized based on the basic movements.

From equation (12) and equation (13), one can note that the rolling velocity of roller unit with index i can be expressed as:

$$v_i = \begin{bmatrix} k & k & kr_i \end{bmatrix} \begin{bmatrix} v_{Px} \\ v_{Py} \\ \omega_P \end{bmatrix}, \tag{14}$$

where k's value varies from 0 to 1 to control the transport speed. The default value of k is 1, which represents the maximum transport velocity of the package.

Based on the expression of rolling velocity in equation (14), one can analyze the package translation, rotation and the combination movements.

5.1.1. Translation control

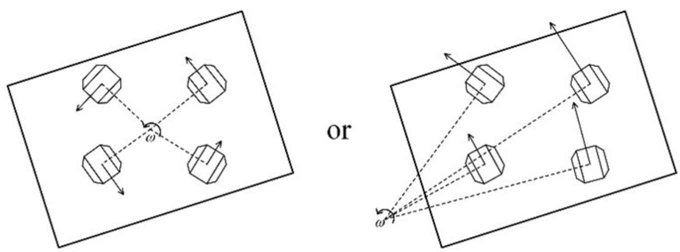
For the package translation control without considering the rotation movement, the package rotation angular velocity ω_P is assumed equal to 0. All the roller units should have the same swiveling angle α_i, which equals the value of transport angle λ.

Therefore, the rolling velocity v_i and the swiveling angle α_i of roller unit for translation control can be expressed as

$$\begin{aligned} v_i &= \begin{bmatrix} k & k & k\sqrt{(x_\mathrm{P}-x_i)^2+(y_\mathrm{P}-y_j)^2} \end{bmatrix} \begin{bmatrix} v_{\mathrm{P}x} \\ v_{\mathrm{P}y} \\ 0 \end{bmatrix}, \\ \alpha_i &= \lambda. \end{aligned} \tag{15}$$

5.1.2. Rotation control

In the case of package rotation control without considering the translation movement, the package rolling velocity v_i equals 0. All the roller units should have the swiveling angle α_i perpendicular to the direction of r_i. The rotation center could be inside or outside the package range (Fig. 6). The swiveling angle α_i should be equal to $\delta_i + \pi/2$, where δ_i is the package angle of each related roller unit (Fig. 3).



Rotation center inside package Rotation center outside package

Fig. 6. Package rotation movement

Therefore, the rolling velocity v_i and swiveling angle α_i of the roller unit for translation control can be expressed as

$$\begin{aligned} v_i &= \begin{bmatrix} k & k & k\sqrt{(x_\mathrm{P}-x_i)^2+(y_\mathrm{P}-y_j)^2} \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ \omega_\mathrm{P} \end{bmatrix}, \\ \alpha_i &= \arctan\big((y_\mathrm{P}-y_j)/(x_\mathrm{P}-x_i)\big) + \pi/2. \end{aligned} \tag{16}$$

5.1.3. Normal transport control

For normal transport of the package, which is the combination of random rotation and random translation, the value of roller unit's rolling velocity v_i and swiveling angle α_i should be determined according to the planned transport trajectory.

If the package transport along the planned trajectory, the package position and posture P_m at moment t_m and t_{m+1} can be expressed as

$$\begin{aligned} P_m &= \begin{bmatrix} x_m & y_m & \theta_m \end{bmatrix}^{\mathrm{T}}, \\ P_{m+1} &= \begin{bmatrix} x_{m+1} & y_{m+1} & \theta_{m+1} \end{bmatrix}^{\mathrm{T}}. \end{aligned} \tag{17}$$

The time interval of package detection and transport control is set to Δt, the time interval between t_m and t_{m+1}, which is short to enhance the control accuracy.

For package transport between moment t_m and t_{m+1}, the position and posture differences can be expressed as

$$P_e = \begin{bmatrix} x_e & y_e & \theta_e \end{bmatrix}^{\mathrm{T}} = \begin{bmatrix} x_{m+1} - x_m & y_{m+1} - y_m & \theta_{m+1} - \theta_m \end{bmatrix}^{\mathrm{T}} \theta \tag{18}$$

The derivative of equation (18) with respect to time expresses the package movement matrix as

$$Q = \begin{bmatrix} \dot{x}_e & \dot{y}_e & \dot{\theta}_e \end{bmatrix}^{\mathrm{T}} = \begin{bmatrix} v_{\mathrm{P}x} & v_{\mathrm{P}y} & \omega_{\mathrm{P}} \end{bmatrix}^{\mathrm{T}}. \tag{19}$$

Then, the package movement can be divided into two parts: translation and rotation (Fig. 7).

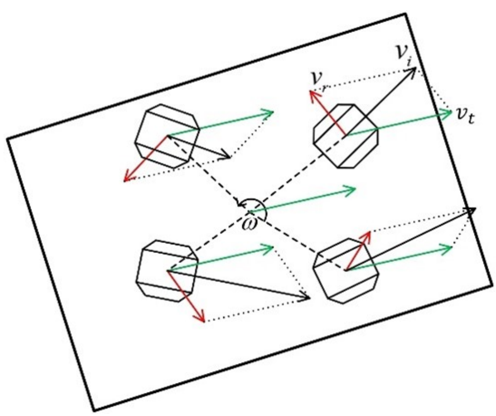


Fig. 7. Normal transportation

For translation movement, the movement matrix can be expressed as

$$\begin{aligned}
v_{\mathrm{P}xt} &= \cos\alpha_t \sqrt{(x_{T_2}-x_{T_1})^2+(y_{T_2}-y_{T_1})^2}/T,\\
v_{\mathrm{P}yt} &= \sin\alpha_t \sqrt{(x_{T_2}-x_{T_1})^2+(y_{T_2}-y_{T_1})^2}/T,\\
\omega_{\mathrm{P}} &= 0,\\
\alpha_t &= \arctan\left((y_{\mathrm{P}}-y_j)/(x_{\mathrm{P}}-x_i)\right).
\end{aligned} \tag{20}$$

Therefore, the translation control part can be expressed as

$$\begin{aligned}
v_t = &\left[k \quad k \quad k\sqrt{((x_{m+1}-x_m)^2+(y_{m+1}-y_m)^2}\right]\\
&\cdot\begin{bmatrix} \cos\alpha_t \sqrt{(x_{T_2}-x_{T_1})^2+(y_{T_2}-y_{T_1})^2} \\ \sin\alpha_t \sqrt{(x_{T_2}-x_{T_1})^2+(y_{T_2}-y_{T_1})^2} \\ 0 \end{bmatrix},\\
\alpha_t = &\arctan\left((y_{m+1}-y_m)/(x_{m+1}-x_m)\right).
\end{aligned} \tag{21}$$

Similarly, for the rotation movement, the movement matrix can be expressed as

$$\begin{aligned}
v_{\mathrm{P}xr} &= 0,\\
v_{\mathrm{P}yr} &= 0,\\
\omega_{\mathrm{P}} &= (\theta_{m+1}-\theta_m)/T,\\
\alpha_t &= \arccos\left((v_e^2+v_t^2-v_r^2)/2v_e v_t\right).
\end{aligned} \tag{22}$$

Therefore, the rotation control part can be expressed as

$$\begin{aligned}
v_r &= \left[k \quad k \quad k\sqrt{(x_{m+1}-x_m)^2+(y_{m+1}-y_m)^2}\right]\begin{bmatrix} 0 \\ 0 \\ (\theta_{m+1}-\theta_m)/T \end{bmatrix},\\
\alpha_r &= \arccos\left((v_e^2+v_t^2-v_r^2)/2v_e v_t\right).
\end{aligned} \tag{23}$$

After combining the translation and rotation movements, the normal transport control for rolling velocity v_e and swiveling angle α_e for roller unit should be

$$\begin{aligned}
v_e = &\left[k \quad k \quad k\sqrt{(x_{m+1}-x_m)^2+(y_{m+1}-y_m)^2)^2}\right]\\
&\cdot\begin{bmatrix} \cos\alpha_t \sqrt{(x_{T_2}-x_{T_1})^2+(y_{T_2}-y_{T_1})^2} \\ \sin\alpha_t \sqrt{(x_{T_2}-x_{T_1})^2+(y_{T_2}-y_{T_1})^2} \\ (\theta_{m+1}-\theta_m)/T \end{bmatrix},\\
\alpha_e = &\arctan\left((y_{m+1}-y_m)/(x_{m+1}-x_m)\right)+\arccos\left((v_e^2+v_t^2-v_r^2)/2v_e v_t\right).
\end{aligned} \tag{24}$$

For the packages of normal transport, the rolling velocity v_e and swiveling angle α_e of relevant roller units should be calculated based on the planned trajectory in real time in regular time intervals.

6. Simulation and experiments

To assess the transport control algorithm, a co-simulation model was established. In the co-simulation, multiple roller units with control algorithm work together to move package along a desired trajectory. Based on the simulation results, one can asses the control algorithm. Then, the experiments are conducted to realize and test the transport platform.

6.1. Co-simulation of transport platform

To assess the control algorithm of a transport platform, a co-simulation based on Solidworks and Adams was conducted. A simplified 3D model (Fig. 8) was established in Solidworks, and the model was then inputted to Adams. The size of package was 30 cm × 30 cm, and the weight was 10 kg. The static friction coefficient was set to 0.5 and the dynamic friction coefficient was set to 0.4.

It is noted that the rotation velocity of the swiveling roller motor changes when it is loaded and unloaded (Fig. 9). Base on the experimental data of a selected

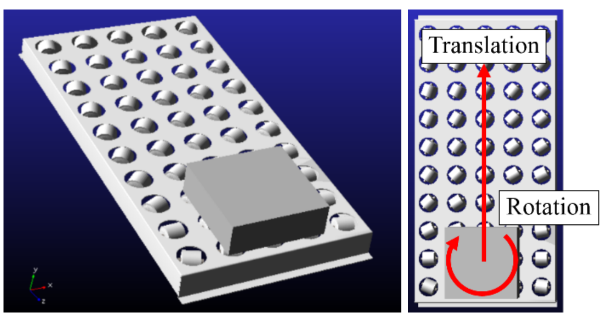


Fig. 8. Simulation model in Adams

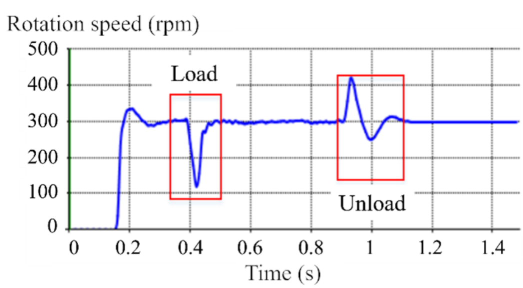


Fig. 9. Characteristics of swiveling roller motor

swiveling roller motor, one can determine the velocity curve of swiveling roller motor in co-simulation (Fig. 10).

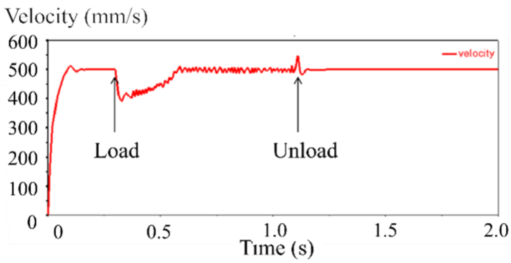


Fig. 10. Rotation velocity of swiveling roller motor in co-simulation model

To test the control algorithm, three basic movements were simulated, including: translation, rotation and combination of both. Note that there was no detection part in the co-simulation model. The package center coordinates and package angle were taken directly from the model.

6.1.1. Translation

The translate velocity of the package was set to 0.5 m/s as the package moved along z direction. Note that the x and y values remained the same, while z value linearly decreased. The package could translate along z direction, as required (Fig. 11). The angular velocity of the package fluctuated at the beginning of translation, which was caused by the acceleration of swiveling rollers. When the swiveling rollers rotated stably, variability of angular velocity decreased. The momentary jump in angular velocity after 0.2 s was caused by the change of the supporting swiveling roller.

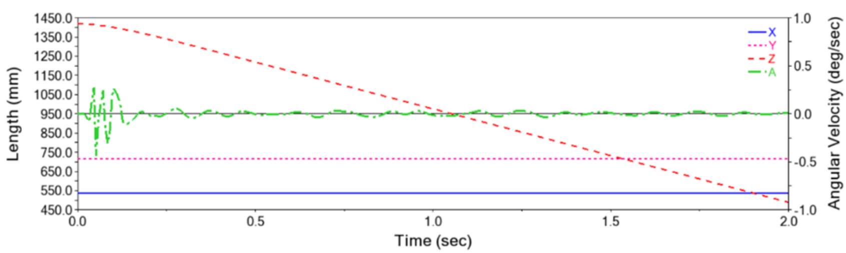


Fig. 11. Package translation simulation

6.1.2. Rotation

Then, as the rotation simulation was conducted, the package was set to rotate about its center with a rotation speed of 1 rad/s (57.3°/s). Note that the package could reach its rotation speed in 0.5 s (Fig. 12). Then, the package rotates at a stable speed, while the x, y and z values remain the same.

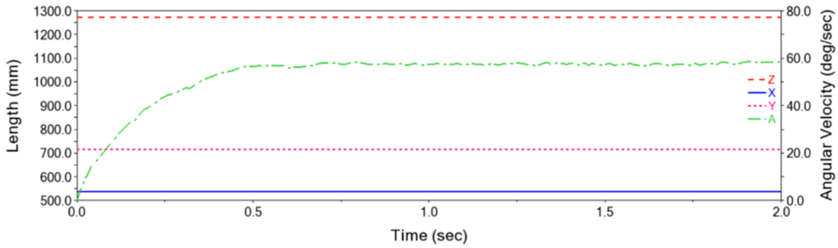


Fig. 12. Package rotation simulation

6.1.3. Combination of translation and rotation

The combination of translation and rotation was also conducted on the co-simulation mode. The package was set to translate along z direction with a velocity of 0.5 m/s and self rotation speed of 1 rad/s (57.3°/s). Note that the package could translate along z direction linearly. Meanwhile, the angular velocity of package would fluctuated at the beginning, increased to the desired value and then remained the same (Fig. 12).

Note that the translation of package can induce fluctuations in angular velocity (Fig. 11 and Fig. 13). When the package moves above the swiveling rollers, the package periodically contacts the incoming new swiveling rollers and detaches from the rear ones. The sudden change of supporting force could induce small oscillations of the package, which influence the package angular velocity.

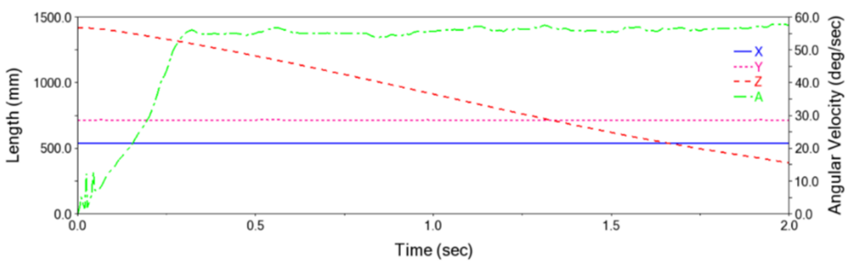


Fig. 13. Package combination movement simulation

6.2. Transportation experiments

The prototype of roller units and a platform were manufactured in order to testify the working performance of the roller array-based package transport and the sorting platform together with its control algorithm,.

Each roller unit (Fig. 14) contains three main parts: a swiveling roller, a swiveling motor and a local controller. The local controller gets commands from the main controller and controls the swiveling roller and the swiveling motor to work with rolling velocity v_i and swiveling angle α_i, respectively. Note that once the roller unit is restarted, the swiveling angle is set to zero by utilizing the origin switch. It can also be noted that the roller unit automatically sets the swiveling roller regularly to the zero position to eliminate the accumulated rotation errors during package transport and sorting process.

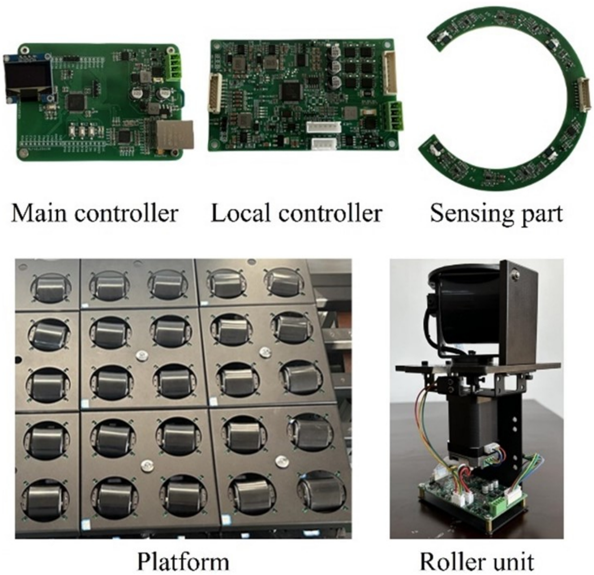


Fig. 14. Photos of experiment equipment

Four photoelectric sensors were integrated on one electric circuit board (Fig. 14). The circuit boards were attached around the roller unit to detect the package. The photoelectric sensors' signal was processed by the local controller and then sent to the main controller for calculation.

All the local controllers (Fig. 14) are connected to the main controller (Fig. 14) via CAN bus. Each local controller sends the information to the main controller periodically, including current sensor's status, rolling velocity and swiveling angle. The main controller utilizes the current information from the local controllers to calculate the working parameters for all roller units for the next step.

To test the working performance, a total of 25 roller units were used to form a 5 by 5 roller unit array as a simple transport platform, and a carton package with a size of 30 cm $\times$ 30 cm and weight of 10 kg was selected as the test object.

6.2.1. Package translation

To test the package translation ability, the package was transported through four consecutive points (Fig. 15), including (120, 120), (120, 480), (480, 480) and (480, 120) ones. The total length of the transport path was 1080 mm. The transport velocity was set to 0.5 m/s.

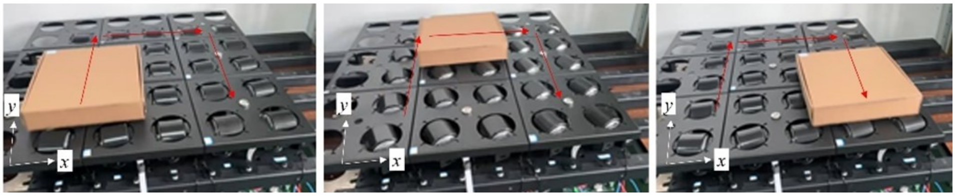


Fig. 15. Package translation experiment

The experiment shows that the transport takes 2.3 s, the transport velocity is 0.47 m/s and the velocity error is 6%, which is acceptable. During the transport process, the package angle remains the same. This experiment shows that the roller array-based package transport and sorting platform can translate packages along a required trajectory with a demanded transport velocity and package angle.

6.2.2. Package rotation and turning

To test the package self-rotation ability, the package was placed on the platform. The package was set to rotate through an angle of 90 degrees at 1 rad/s around its geometry center (Fig. 16). Then, to test the package turning ability, the package was placed first on the left corner and rotated around the right corner of the platform (Fig. 17), then, the package was placed on the right corner and rotated around the left corner of the platform (Fig. 17).

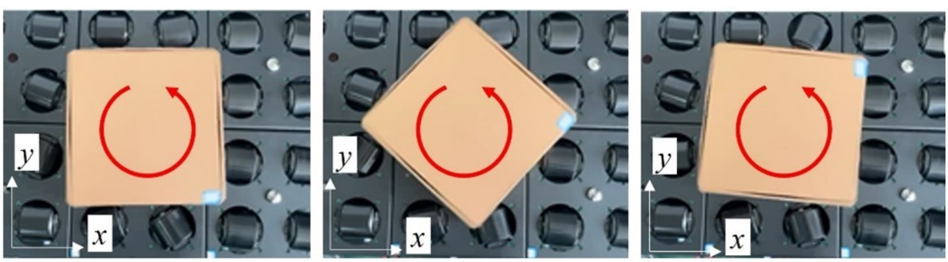
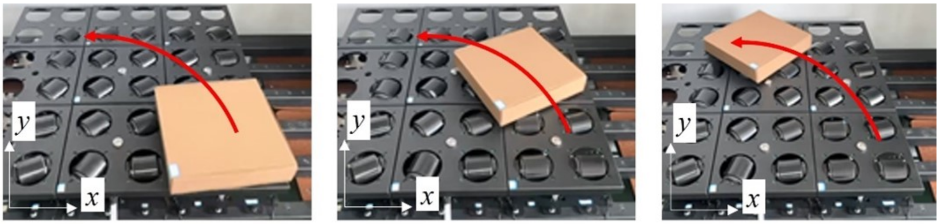
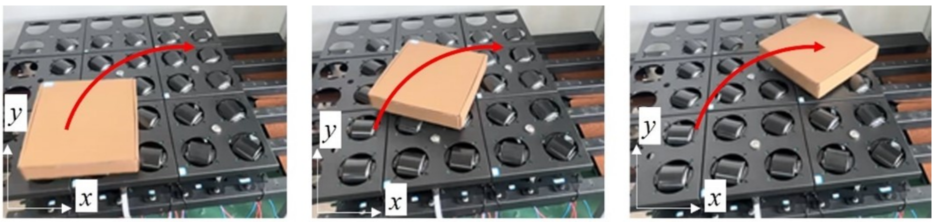


Fig. 16. Package rotation experiment

The experiment shows that self-rotation takes 1.5 s, the actual rotation angular velocity is 1.05 rad/s and the relative error is 5%, which is satisfactory for the requirement. During the self-rotation process, the center of the package remained unmoved. The turning experiment also shows that the package can rotate around a certain point on the platform. The experiment results show that the roller array-based package transport platform can rotate packages along a required trajectory with a demanded rotation angular velocity and rotation angle, which can be used for package sorting.



(a) Left turning experiment



(b) Right turning experiment

Fig. 17. Package turning experiment

6.2.3. Package transport

To further test the package transport ability, the combination of translation and rotation movement was tested. The package was planned to be transported along an ‘S’ shape trajectory’ (Fig. 18).

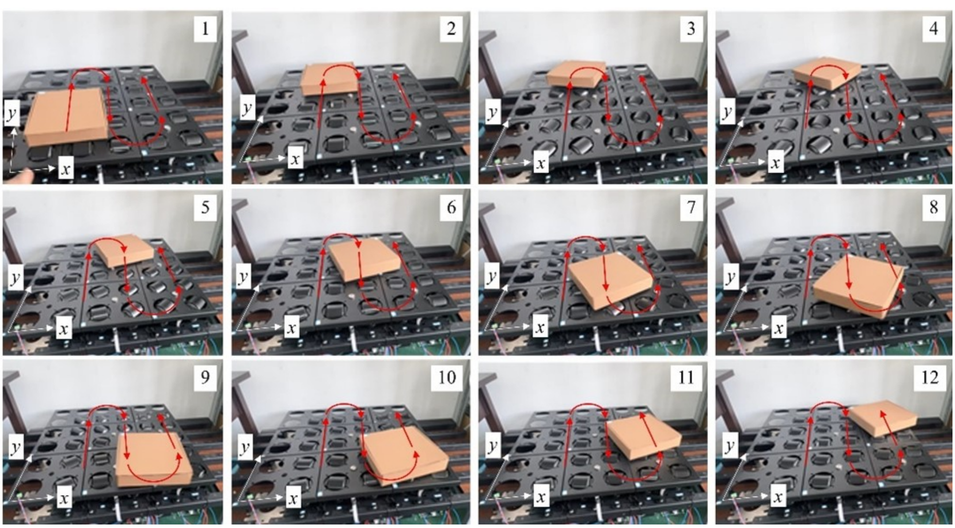


Fig. 18. Package transport experiment

The control for 'S' shape transport requires detection of the package in real time to correct the rolling velocity v_e and the swiveling angle α_e (equation (24)) of each roller unit regularly.

The experiment shows that the package can move along the planned trajectory. Therefore, the roller array-based transport platform can successfully control the transport of the package and thus help package sorting.

6.3. Experimental analysis

The experimental results show that the transport platform can work. However, the movement of package in the transport experiment was not as accurate as that in co-simulation. In the package transport experiments (Fig. 15–18), the package center and package angle were not the same as the ones planned during the transport process.

It is noted that the movement error was induced by the package detection process. The Matlab was used for simulation, in which a package with a width of 360 mm and a length of 480 mm was placed on the platform 10000 times. Each time the package was randomly placed, with a random package center and package angle (Fig. 19). For each case, the real center and the calculated center were compared to one another to determine the center difference. The real package angle and the calculated package angle were also compared. The results showed that the distance between the real package center and the planned one could be as large as 19.6 mm, and the package angle difference could be as large as 35.1°.

It is noted that the detection part cannot provide accurate package boundary information, it can only provide the sensors' position nearest the package boundary. In some cases, maximum and minimum X and Y values provided by the sensor weren't close to the four corners (Fig. 19). This induces errors in calculation of package center and package angle.

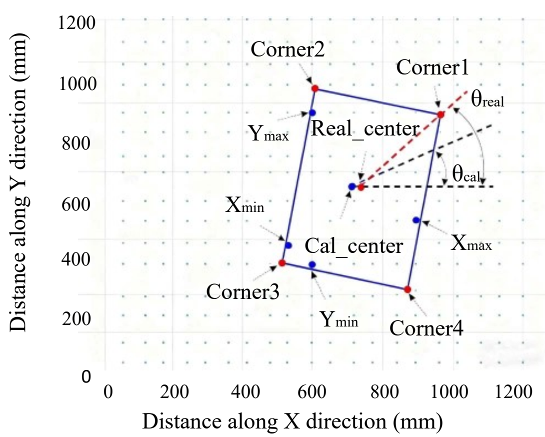


Fig. 19. Package center and angle differences

For a single package transport and sorting, a certain movement error is acceptable, since there is usually a guide plate applied to correct the package transport position and angle. However, for package merging, sequencing and aligning, the movement error is not acceptable. Incorrect package position and posture detection cause package interference and collision during the transport process. For future work, more accurate detection method should be used to minimize the package movement error.

7. Comparison with existing solutions

The new proposed platform, in practical application, will not replace the entire logistics conveyor line, but only a certain critical component of it. Thanks to the platform's versatility, it could enhance the practicality, flexibility, convenience, and cost-effectiveness of an existing logistics conveyor system.

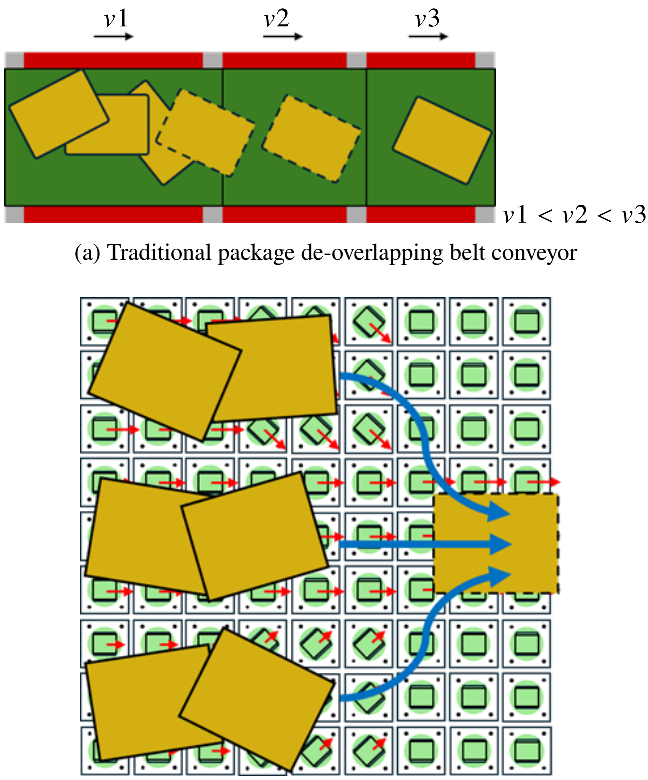
(1) Practicality: The proposed platform integrates multiple functions, including de-overlapping, aligning, diverting/merging and sorting capabilities. The multifunctional platform could enhance its practicality, allowing it to perform diverse roles across various scenarios. Compared with the existing logistic equipment, it features easy installation and setup, and ensures a higher working efficiency.

For a de-overlapping process (Fig. 20), the existing solution utilizes multiple belt conveyors with different transportation speeds to adjust the space between packages. This solution could only transport packages one by one. However, the newly proposed platform could transport multiple packages at the same time with different velocity and direction, which would improve its working efficiency.

For an aligning process (Fig. 21), the existing solution utilizes a guiding plate to change the orientation of moving packages. When the package size changes, the position/shape of the guiding plate should also be adjusted. The proposed platform could utilize multiple roller units to control the orientation of each package at the same time. The package boundaries are detected by the sensors; therefore, the change of package size doesn't influence the aligning process. The platform can align multiple packages at the same time. Then, the working efficiency of package alignment can be significantly improved by the proposed platform.

For a diverting/merging process (Fig. 22), the traditional solution would utilize a steering wheel sorter equipment or an oscillating mechanism to help the package divert/merge at a certain position. The proposed platform could track a certain package and conduct the diverting/merging process with the planed package moving trajectory.

For the package sorting process (Fig. 23), the traditional solution usually utilizes slide blocks to push the package out of the conveyor and into the collection devices. The position of slide blocks and collection devices are fixed. The package size cannot be changed. For the proposed platform, the package would not be subjected to sudden pushing forces. Also, the package size/weight won't be limited



(a) Traditional package de-overlapping belt conveyor

(b) De-overlapping process based on proposed platform

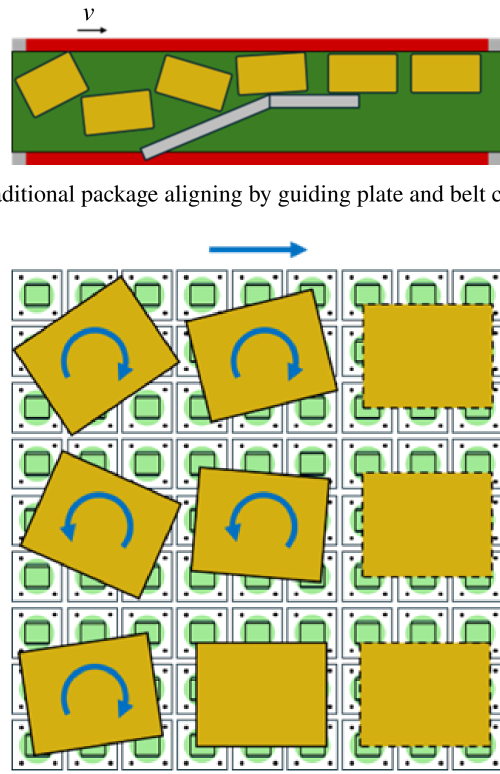
Fig. 20. Package de-overlapping

by a slid block. Besides, by changing the software parameters, both the size and position of collection devices could be reconfigured.

The prosed platform could be used to replace multiple kinds of logistic equipment. It is more practical than the existing solutions, and it can improve working efficiency.

(2) Flexibility: The design and manufacturing of traditional logistics conveyors system require consideration of multiple factors such as facility layout, package type, and usage scenarios. Such system usually have limited adaptability. If changes occur in the facility layout, the type of package changes, or if the logistics conveyors system requires expansion or re-layout, the feasibility must be carefully reevaluated. Most of the time, the existing traditional equipment cannot satisfy the requirements of changes, therefore redesigning and remanufacturing are necessary.

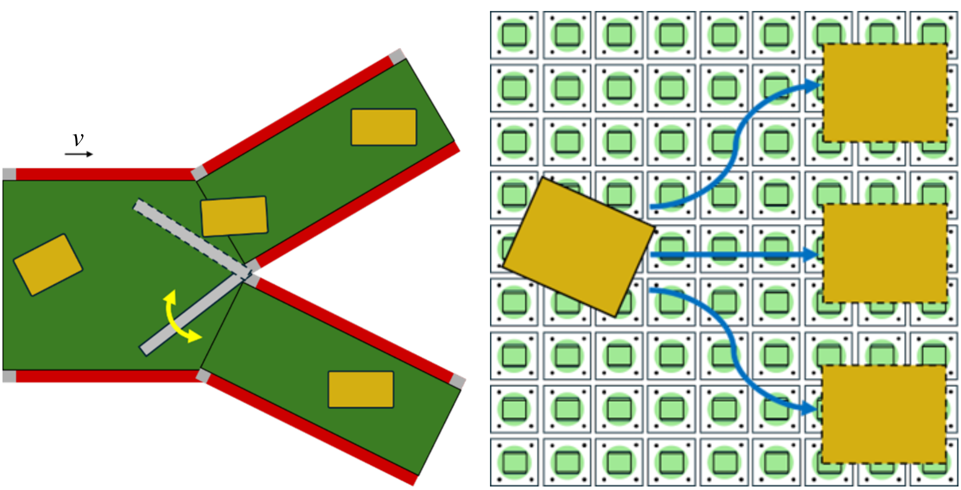
In contrast, the proposed platform is composed of fundamental units. These modular units can be freely combined and configured according to requirements, allowing the platform size and layout to be easily reconfigured. It can adapt to the changes of the facility layout or the type of package. It can also work when the logistics conveyors system requires expansion or re-layout. This adaptation can be



(a) Traditional package aligning by guiding plate and belt conveyor

(b) Aligning process based on proposed platform

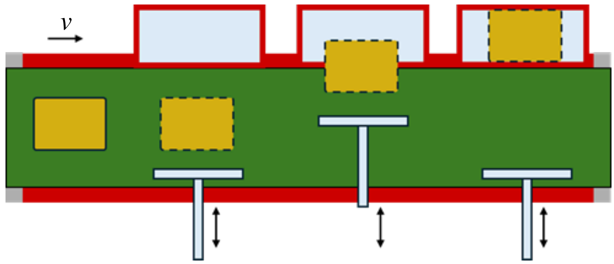
Fig. 21. Package alignment



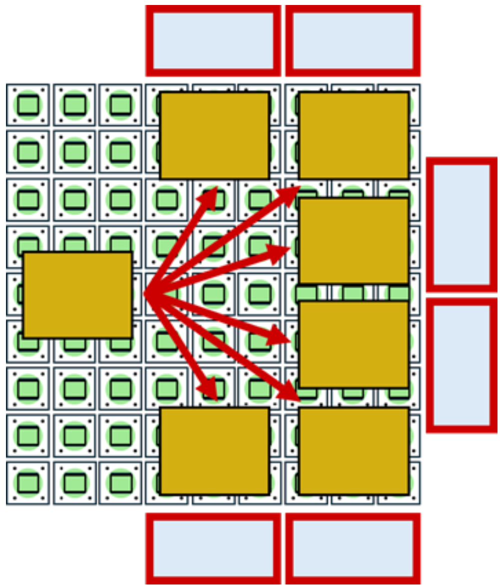
(a) Traditional package diverting by oscillating mechanism and belt conveyor

(b) Diverting process based on proposed platform

Fig. 22. Package diverting



(a) Traditional package sorting by guiding plate and belt conveyor



(b) Sorting process based on proposed platform

Fig. 23. Package sorting

achieved by adding or removing the modular units and updating the software configuration. Furthermore, the adaptation could be achieved without redesigning and remanufacturing. Thus, the proposed platform significantly enhances the flexibility of the logistics conveyor system.

(3) Convenience: For traditional logistics conveyor system, due to the different facility layout, package type and conveying requirements, most of the critical equipment is custom-built. The manufacturers usually do not stock the key equipment in advance. Furthermore, when the custom-built equipment requires maintenance or repair, the varied types and models demand professional skills, which can be complicated.

However, the new platform consists of standardized basic roller units of the same model, enabling large-scale mass production and inventory stocking without the need for customization. When a logistics conveyor system needs to be established, these basic units can be used immediately, eliminating the time for custom manufacturing.

For maintenance or repairs, only general technical personnel are required to conduct modular unit maintenance or replacement. Since the maintenance and repair are performed on an individual module unit separately, it would not disrupt the normal operation of the entire conveyor system. This is significantly important for critical conveyor system that cannot be stopped.

(4) Cost-effectiveness: Compared with traditional equipment, the new proposed platform is modularly manufactured with a single model type, eliminating the need for customization. This allows large-scale mass production, which significantly reduces the costs. Furthermore, the roller unit can be stocked in advance and deployed flexibly according to the actual requirement. This would shorten production cycles and enhance profitability. Additionally, the platform can be installed and adjusted on the bases of on-site conditions. Configuration could be performed by software, therefore reducing the costs of field installation.

Maintaining and repairing the proposed platform does not require specialized technical personnel familiar with all the conveyor equipment. Also, troubleshooting can be solved by replacing the module unit. It greatly reduces the costs of maintenance and repairs. Unlike the traditional equipment, if an individual module fails to work, there is no need to halt the entire conveyor system. The software could reroute packages around the affected area, the failed module can be replaced individually, which ensures uninterrupted operation of the conveyor system and reduces the failure cost.

Moreover, the proposed platform integrates multiple functions, which means a single platform could perform several tasks simultaneously. For example, it can align package while de-overlapping and sorting packages. This reduces the requirement for facility space and production costs. Finally, the proposed platform could operate with a higher efficiency compared to the traditional equipment. It could process multiple packages at the same time, which would boost throughput and increase the overall revenue.

8. Conclusions

This paper proposed a roller array-based transport and sorting platform, which utilizes the roller unit to control the movement of packages. The roller array-based transport and sorting platform proposes a flexible and adaptable solution for package transport. The size, function, and trajectory of platform can be modified according to requirements.

The roller unit was introduced. This modularly designed roller unit could utilize swiveling roller and swiveling motor to control the movement of package.

Meanwhile, the package detection technology was introduced. This technique could help detecting the geometry center of packages and prevent the influences of factors such as package material, package color, surface curvature, residual sticker and environmental light source.

The package transport control algorithm based on roller unit array was proposed. For package translation, rotation, turning and normal transport requirement, the control algorithm helps calculating relevant rolling velocity and swiveling angle for every roller unit. Therefore, the roller units can cooperate with each other to guarantee the package movement trajectory.

Finally, co-simulation and experiments were conducted to testify the ability of roller array-based transport and sorting platform. The platform can successfully translate, rotate, turn and transport packages along a planned trajectory.

The proposed platform was compared with the existing solutions and it showed several advantages.

For future work, the performance of a larger platform should be tested to inspire confidence for a real case. The algorithm for multiple packages movement control should also be analyzed for collecting, separating, merging, sequencing and aligning of packages. Besides, it is noted that although the existing package detection technique helps controlling the movement of transport, the detection accuracy should be improved for a more precise package movement control.

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