Development of a Foreign Material Removal System Using an Object Detection Algorithm

AUTHOR

Shinya YASUDA

ABSTRACT

In recent years, contamination by foreign materials has become a significant issue in various granular materials, including recycled raw materials, plastic resin pellets, and agricultural products, from the perspectives of product quality, safety, and equipment reliability. Foreign materials are typically identified and manually removed from granular materials flowing on belt conveyors (hereinafter referred to as "bulk materials"). However, this task imposes a substantial workload on operators, and the sorting accuracy often depends on the skill and experience of individual workers. Consequently, there is an increasing demand for automation and labor-saving solutions.

This paper describes the development of a foreign material removal system in which a camera captures images of granular materials conveyed on a belt conveyor and an object detection algorithm is applied to the captured images to identify the locations of foreign materials mixed within the material stream. Based on the detection coordinates, a suction nozzle is controlled to remove the foreign materials. Specifically, a series of design procedures (design flow), including coordinate transformation and timing compensation, was developed to convert detection coordinates obtained from camera images into a conveyor coordinate system and encoder pulses, and to actuate the nozzle at the appropriate timing while accounting for image-processing and communication delays.

The developed system was evaluated using an in-house simulated production line. The results demonstrated high performance in terms of both detection rate and removal rate for foreign materials with sizes ranging from approximately 1 to 10 mm. Furthermore, design guidelines for control parameters were investigated for cases under different belt conveyor speeds and suction nozzle arrangements. The proposed technology is applicable not only to recycled materials but also to resin pellets, agricultural products such as grains and beans, animal feed, and other bulk materials transported on conveyor lines. Specifically, the proposed technology is expected to be applicable to foreign-material removal processes involving bulk materials flowing on belt conveyors, including removal during conveying, preprocessing for sorting operations, and removal prior to packaging and filling.

1. Introduction

1.1 Background

In conveying, sorting, and processing operations involving bulk materials such as recycled raw materials, resin pellets, agricultural products, and animal feed, contamination by small foreign materials can lead to product quality deterioration and operational problems in downstream processes. For example, the presence of small metal fragments, stones, or glass particles may cause equipment damage or product defects during subsequent molding, crushing, or thermal treatment processes such as drying and firing. Consequently, many production lines incorporate inspection and removal processes to detect and eliminate foreign materials before they reach downstream operations[1].

Conventionally, foreign materials in bulk materials flowing on belt conveyors have been removed through manual visual inspection and hand-picking, as well as through automated sorting equipment such as color sorters and metal detectors. However, visual inspection and manual removal are highly dependent on the skill, experience, and concentration of individual operators, making them susceptible to fatigue and oversight during prolonged operation. In addition, sorting systems based on simple sensors, such as photoelectric sensors and proximity sensors, may have difficulty detecting certain types of foreign materials depending on their material, shape, or size. Furthermore, increased throughput (the amount of material fed per unit time) resulting from increased production volumes and higher line speeds, together with labor shortages, has made it increasingly difficult to maintain stable product quality using these conventional methods alone.

In light of these circumstances, in recent years, object-detection technologies utilizing machine learning for camera image recognition have been introduced into foreign-material inspection and sorting systems, enabling both adaptability to changes in target objects and inspection conditions and high detection performance[1]. In the present development, the target foreign materials are small contaminants with sizes ranging from approximately 1 to 10 mm that are mixed within bulk materials.

1.2 Challenges and Consideration of Removal Methods

When designing a system to automatically remove small foreign materials approximately 1–10 mm in size from bulk materials flowing on a belt conveyor, one of the most important considerations is the selection of an appropriate removal method. Representative approaches include the following:

1. Air-Jet Removal Method

This method is widely employed in optical sorting systems, for example. Foreign materials detected by a camera or sensor are removed by momentarily discharging compressed air through a nozzle positioned downstream of the detection point. The air jet deflects the detected foreign material from the material stream on the belt conveyor and ejects it outside the conveying path. This method is capable of high-speed processing when the foreign materials are several millimeters or larger in size and exhibit differences in specific gravity or shape from the target materials. It also allows the sorting criteria to be adjusted easily to accommodate changes in the objects to be sorted.

2. Mechanical Flapper Chute Method

In this method, a gate or flapper is installed at the discharge end of a belt conveyor or within a chute, and the falling trajectory of conveyed materials is switched by opening and closing the gate or flapper. The mechanism is relatively simple and is well suited for sorting large bulk objects or packaged products. However, it is generally difficult to selectively separate small foreign materials from the main material stream.

3. Robot-Arm Picking Method

In this method, foreign materials detected by a camera are grasped and removed using a robot arm, providing a high degree of flexibility and versatility. However, considering the cycle times of current industrial robots, it is difficult to apply this method to applications requiring the pickup of numerous small foreign materials, approximately 1–10 mm in size, from bulk materials moving at high speed on a belt conveyor.

The foreign materials targeted in this development are small particulate objects approximately 1–10 mm in size that flow on a conveyor while mixed with acceptable materials. Under such conditions, the air-nozzle blow-off method, which has been widely used in conventional systems, presents several challenges:

- Due to the dispersion of the air jet, there is a high risk of unintentionally blowing away the acceptable materials together with the foreign materials around them.
- Small foreign materials with high specific gravity (e.g., fine metal fragments), as well as foreign materials buried within the bulk materials or located near the belt surface, may not be effectively removed because the airflow has limited influence on them.
- Under high-throughput conditions, continuous air-jet discharge may disturb the distribution of surrounding particles, potentially affecting subsequent removal operations.

In contrast, the suction-nozzle method generates localized negative pressure using compressed air or a vacuum source to draw target objects into the nozzle. By positioning the nozzle close to the belt surface, the following advantages can be obtained:

- The suction region can be localized near the nozzle opening, thereby minimizing the impact on acceptable materials.
- The suction direction is nearly perpendicular to the belt surface, and stable removal can be expected even for small and heavy foreign materials.
- The system configuration, including piping, valves, and removal actuators (suction nozzles), is similar to that of the air-nozzle method, allowing existing air-supply infrastructure to be readily utilized.

Particularly when processing small foreign materials in the size range of 1–10 mm under high-throughput conditions, as targeted by the present system, the suction method is a promising alternative to the blow-off method

because, depending on the operating conditions, it can achieve a high removal rate while reducing the unintended removal of acceptable materials. In addition, in order to control the suction nozzle based on the location of foreign materials, a detection method capable of outputting foreign-material coordinates is required. Therefore, object detection was adopted, as it can directly provide the locations of multiple foreign materials and can be easily extended to newly added target objects through additional training.

However, even when the object-detection-based suction method is employed, several technical challenges remain at the system level.

- Detection of Small Foreign Materials

Many target foreign materials are small, approximately 1–10 mm in size, and may have appearances similar to those of the surrounding bulk materials. To achieve stable detection from camera images under such conditions, appropriate design of imaging conditions (e.g., resolution, field of view, illumination, and background color) and suitable selection and training of the object detection algorithm are required.

- Suction Timing Control Based on Detection Results

Foreign materials are conveyed on a moving belt. Accordingly, a time delay exists between image acquisition and the moment when the detected foreign material passes beneath the suction nozzle. It is therefore necessary to accurately predict the arrival time of each detected foreign material at the nozzle position while considering detection processing time, communication delays between the PC and PLC, PLC scan time, and the like.

- Control for Multiple Foreign Materials and Multiple Nozzles

In high-throughput production lines, multiple foreign materials may be present on the conveyor simultaneously. Furthermore, multiple nozzles may be required to improve removal performance. In such cases, a control logic is required to determine which nozzle should be actuated, for which foreign material, and at what timing.

- Trade-off Between Acceptable Material Loss and Removal Efficiency

Increasing the nozzle diameter or suction intensity generally improves foreign-material removal efficiency; however, it also increases the amount of acceptable materials unintentionally removed. To improve foreign-material removal performance without reducing productivity, it is important to establish a design that balances nozzle design parameters (diameter, height, and arrangement) and control parameters (suction duration, actuation timing, and suction pressure).

These challenges are common to a wide range of systems designed to detect and remove small foreign materials from bulk materials flowing on belt conveyors, regardless of the type of foreign material or industrial field. In this paper, these challenges are organized as a design method for a foreign-material removal system employing suction nozzles.

1.3 Objective of the Present Development

The objective of the present development is to prototype a foreign-material removal system for bulk materials flowing on a belt conveyor using coordinate information of detected foreign materials obtained through an object detection algorithm, and to clarify the design method and fundamental performance of the proposed system.

Specifically, this paper focuses on the following aspects:

- A method for converting the detection coordinates of foreign materials in camera images into the conveyor coordinate system and encoder pulses,
- A method for calculating nozzle actuation timing while accounting for detection processing time and communication delays,
- The configuration of a control logic capable of handling multiple foreign materials and multiple suction nozzles, and
- Evaluation of detection performance and removal performance using an in-house simulated production line constructed based on the above-described design method.

Through these investigations, the paper aims to establish the design process as a standard, industry-independent design procedure covering the entire process from foreign-material detection coordinates to nozzle control.

2. Investigation of the Foreign Material Detection Unit

2.1 Requirements

The foreign material detection unit of the proposed system is responsible for detecting small foreign materials, approximately 1–10 mm in size, in real time from bulk materials flowing on a belt conveyor.

The main requirements for the foreign material detection unit are as follows:

- Target foreign material size: approximately 1–10 mm
- Target foreign materials: metal fragments, plastic fragments, and other heterogeneous material fragments mixed with the bulk materials
- Target detection rate: 90% or higher for the target foreign materials
- Operating conditions:
  a. Continuous processing of bulk materials in motion on a belt conveyor
  b. Throughput varies depending on the production line. However, the system shall be capable of real-time processing at the specified belt speed.
- Output requirements:

For each detected foreign material, the system shall output its position (coordinates) and type (class) in a form that can be utilized by the downstream nozzle control unit. Specifically, in addition to the detection location in the image, the output shall be provided in a format that can be converted into the conveyor coordinate system and encoder pulse counts used for nozzle control.

To satisfy these requirements, the foreign material detection unit was configured with (1) an image acquisition unit including a camera and a lighting system, and (2) an image processing unit (object detection unit) that estimates the positions and types (classes) of foreign materials from the acquired images.

For the development of the foreign material detection unit, the applicability of the object detection algorithm to foreign material detection was evaluated based on the following criteria:

1. Foreign materials with sizes ranging from 1 to 10 mm can be detected.
2. A detection rate of 90% or higher can be achieved based on the total number of foreign materials.

2.2 System Configuration

Figure 2-1 shows a schematic configuration of the foreign material detection unit.

- An area camera was installed above the belt conveyor in a top-view configuration to capture images vertically downward relative to the conveyor travel direction.
- To establish a uniform illumination environment, ring lighting or bar lighting was arranged around the camera to provide uniform illumination of the belt surface and the surface of the bulk materials.
- Still images were acquired at fixed intervals in response to trigger signals as the bulk materials passed through the camera's field of view.

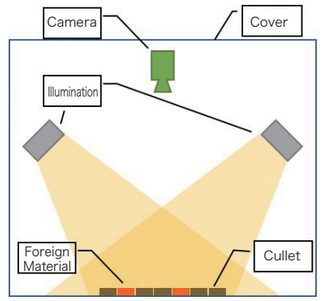


Figure 2-1 Overview of the Foreign Material Detection Unit

In this study, because the flow of bulk materials was nearly continuous and the target foreign materials were relatively small (approximately 1–10 mm in size), the following configuration was adopted:

- an area-camera system for capturing the entire field of view in a single image, and
- a combination of a high-resolution image sensor and a fixed-focus lens.

Compared with a line-scan camera system, this configuration offers a simpler optical design and allows the field of view and image resolution to be adjusted more easily during the prototyping stage.

2.3 Design of Imaging Conditions

(1) Spatial Resolution and Field of View

To achieve stable detection of foreign materials, it is necessary to secure a sufficient number of pixels for the smallest target foreign material. In this study, the minimum target foreign material size was set to 1 mm,

and the camera field of view and image resolution were selected such that the foreign material would be represented by at least 10 pixels in the acquired image.

- Conveyor-width direction: The camera installation height was determined such that the entire effective width of the processing area could be covered by a single camera.
- Conveyor-travel direction: The field of view was determined based on the nozzle-control requirements described later, while ensuring that the imaging length per frame did not become excessively large.
- Spatial scale: The spatial scale (mm/pixel) was determined based on the camera resolution and field of view, using a criterion that a minimum foreign material size of 1 mm should be represented by approximately 10 pixels.

These settings were selected to ensure that the boundaries between foreign materials and acceptable materials were sufficiently represented, thereby providing conditions for stable detection by the downstream object detection algorithm.

(2) Motion Blur and Shutter Speed

Because the bulk materials on the conveyor move at a constant speed, a long exposure time can result in motion blur[2], causing the contours of foreign materials to become unclear. Therefore, in this study, the exposure time was determined such that the motion blur caused by conveyor movement during exposure (hereinafter referred to as "blur") was limited to within one pixel in the captured image.

Let v[mm/s] denote the belt speed, T[s] the exposure time, N[pixels] the number of pixels in the conveyor travel direction of the camera image, and L[mm] the corresponding physical field-of-view length. Then:

- the spatial scale corresponding to a single pixel is given by:

$$\Delta x = \frac{L}{N}\ [mm/pixel]\ , \text{and}$$

- the image displacement during the exposure time is given by:

$$\Delta L = vT\ [mm]\ .$$

In this study, to obtain:

$$\Delta L = \Delta x\ ,$$

that is,

$$vT = \frac{L}{N},$$

the upper limit of the allowable exposure time T was calculated for the assumed maximum belt speed, and the exposure time was set within the resulting allowable range. The exposure time was thus set so that motion blur would remain within one pixel in the image, allowing degradation of object contours to be practically neglected. The loss of image brightness associated with the reduced exposure time was compensated for by increasing the illumination intensity and adjusting the camera gain (hereinafter referred to as gain compensation), thereby maintaining sufficient contrast between foreign materials and the background.

(3) Illumination Conditions

The surface reflectance and color characteristics of foreign materials vary significantly depending on their type and material. Accordingly, illumination conditions and background color have a substantial impact on detection performance.

- Illumination method:
  Diffuse illumination was employed as the primary lighting method to achieve a uniform illumination distribution. When necessary, oblique illumination and polarizing filters were combined to decrease highlights and specular reflections from metallic foreign materials[3][4].
- Background color:
  The color tones of both the bulk material and representative foreign materials were examined in advance, and a belt color (e.g., black, blue, or white) for sufficient contrast with both was selected.
- Image contrast adjustment:
  Camera exposure, gain, and white balance were adjusted to ensure adequate differences in brightness and color between foreign materials and the background.

For these conditions, multiple combination patterns were evaluated using an in-house simulated production line. Foreign material detection rate and false detection rate were used as evaluation metrics, and the optimal combination was selected by considering both the detection rate and the false detection rate.

2.4 Object Detection Algorithm

In the proposed system, a deep learning–based object detection algorithm was employed to automatically estimate the locations and classes (types) of foreign materials from captured images. The object detection algorithm generates multiple candidate regions from an input image and simultaneously estimates, for each region, whether it is a foreign material and the class of the foreign material.

The algorithm adopted in this study employed a Convolutional Neural Network (CNN) as the backbone network. Feature maps extracted at multiple resolutions were integrated, and a one-stage detection framework was used to output bounding boxes and class probabilities for each image region. This architecture enabled real-time inference on continuous image streams acquired from the belt conveyor while maintaining high detection accuracy.

Figure 2-2 shows an overview of the object detection process[5].

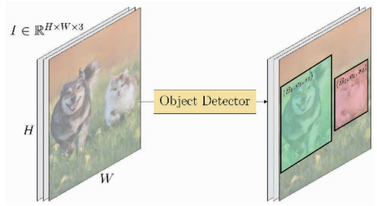


Figure 2-2 Overview of the Object Detection Algorithm[2]

1. Preprocessing
   The captured image is resized to a predetermined input size, and pixel values are normalized. When necessary, brightness and contrast correction as well as noise-reduction filtering are applied.
2. Feature Extraction
   Using a CNN backbone network, hierarchical features such as edges, textures, and shapes are extracted from the input image through multiple layers.
3. Candidate Generation by the Detection Head
   Using feature maps at multiple resolutions, bounding box candidates are generated for each image region. At the same time, the probability that each candidate corresponds to a foreign material and the confidence score for each class are estimated.
4. Post-processing (Thresholding and Non-Maximum Suppression)
   Only candidates whose confidence scores exceed a predetermined threshold are retained. Candidates with substantial overlap are merged through Non-Maximum Suppression (NMS) to obtain the final detection results.

The final output consists of the bounding box coordinates (x_{min} , y_{min} , x_{max} , y_{max}), class label, and confidence score of each detected foreign material in the image coordinate system. In this paper, the center coordinates of each bounding box were defined as the detection coordinates. These coordinates were subsequently transformed into the conveyor coordinate system and encoder pulses, and were then used for suction nozzle control.

2.5 Detection Performance Evaluation

This section describes the performance evaluation of the developed foreign material detection unit. The evaluation was conducted in two stages: an offline evaluation using still images and an online evaluation using images acquired while the belt conveyor was in operation.

(1) Evaluation Metrics

The following metrics were primarily used for the quantitative evaluation of foreign material detection performance.

- Detection Rate

The detection rate was defined as the percentage of target foreign materials that were correctly detected by the object detection algorithm.

$$\text{Detection Rate}[\%] = \frac{\text{Number of correctly detected foreign materials}}{\text{Number of target foreign materials}} \times 100$$

- False Detection Rate

The false detection rate was defined as the percentage of detection results output by the algorithm that did not correspond to actual foreign materials.

$$\text{False Detection Rate}[\%] = \frac{\text{Number of falsely detected foreign materials}}{\text{Total number of detections}} \times 100$$

Evaluation metrics such as precision, recall, and Average Precision (AP) were calculated as reference values when necessary and were used to examine the behavior of the algorithm under different detection thresholds[6].

(2) Offline Evaluation

First, ground-truth data were generated through annotation of still images captured on the in-house simulated production line, and an offline evaluation was conducted using these data as references. The evaluation dataset consisted of multiple test patterns with varying foreign material sizes and placement conditions, and the

detection rate and false detection rate were calculated for each pattern.

The results confirmed that, under the standard operating conditions assumed for practical operation, the target detection rate of 90% or higher was achieved for foreign materials ranging in size from approximately 1 to 10 mm. In addition, the false detection rate was confirmed to be sufficiently low so as not to interfere with the subsequent suction-based removal process (Chapter 5).

(3) Online Evaluation

Next, an online evaluation was conducted with the belt conveyor in operation while bulk material was continuously supplied. The system was operated at a predetermined belt speed for a specified period, and the detection rate was calculated from the number of foreign materials introduced during the test and the number of foreign materials detected.

In the online evaluation, additional factors not included in the offline evaluation were present, such as slight variations in illumination conditions and changes in the overlap and accumulation states of the bulk material. However, under the standard operating conditions assumed for practical operation, a detection rate comparable to that obtained in the offline evaluation was achieved. These results confirmed that the imaging conditions and object detection algorithm designed in this study function effectively in an actual operating environment (Chapter 5).

3. Design of the Control System from Detection Coordinates to Nozzle Actuation

This chapter describes the design method used to determine the actuation timing of the suction nozzle based on the detection coordinates output by the foreign material detection unit described in Chapter 2. Specifically, coordinate transformations from the image coordinate system to the conveyor coordinate system and encoder pulses, timing calculations that account for system delays, and control logic for handling multiple foreign materials and multiple nozzles are detailed.

3.1 Definition of Coordinate Systems

In the proposed system, the following three coordinate systems are defined for representing the positions of foreign materials.

- Image Coordinate System (u, v)

  This coordinate system corresponds to the pixel array of the area camera and is represented by pixel indices. The horizontal pixel position is denoted by u [pixel], and the vertical pixel position is denoted by v [pixel].

- Conveyor Coordinate System (X, Y)

  This coordinate system represents positions in the physical space on the belt conveyor. The conveyor travel direction is defined as X [mm], and the conveyor width direction is defined as Y [mm]. A reference position within the camera field of view is taken as the origin.

- Encoder Coordinate System (E)

  This is a one-dimensional coordinate system in which position is represented by the pulse count acquired from an encoder installed along the conveyor travel direction. The encoder pulse count is denoted by E [pulse], and the instant at which an object passes a specified reference position is defined as $E=0$.

The center coordinates of the bounding box output by the object detection algorithm are given in the image coordinate system (u, v). This chapter describes the procedure for transforming these coordinates into the conveyor coordinate system (X, Y) and subsequently combining them with the encoder coordinate E to calculate the actuation timing of the suction nozzle.

3.2 Conversion from Image Coordinates to Conveyor Coordinates

The camera is fixed above the belt conveyor. Accordingly, the plane within the camera field of view can be regarded as being approximately parallel to the conveyor surface. Therefore, a correspondence between the image coordinate system (u, v) and the conveyor coordinate system (X, Y) can be defined using a projective transformation (homography) or an affine transformation.

In this study, a calibration pattern with known dimensions was placed within the camera field of view. After obtaining corresponding points between (u, v) and (X, Y) from multiple points on the pattern, the coordinate transformation equations were determined using the following linear model.

- Conveyor coordinate system

$$X = a_{11}u + a_{12}v + a_{13}$$
$$Y = a_{21}u + a_{22}v + a_{23}$$

where a_{ij} are coefficients determined through calibration. During the calibration process, markers were placed at both edges of the conveyor width and at multiple positions along the conveyor travel direction. By establishing correspondences between the marker positions and their pixel coordinates in the image, the transformation parameters were determined so that the coordinate conversion error remained within an acceptable range throughout the entire field of view.

The object detection algorithm provides a bounding box and its center coordinates (uc, vc). These coordinates are converted into conveyor coordinates (Xc, Yc) using the coordinate transformation described above.

3.3 Conversion of Conveyor Movement into Encoder Pulses

In controlling the suction nozzle, it is necessary to accurately predict the time at which a foreign material passes directly beneath the nozzle. In the proposed system, pulse signals generated by an encoder attached along the conveyor travel direction are monitored, and the cumulative pulse count is converted into and managed as the conveyor travel distance.

The encoder specifications are defined as follows:

Number of pulses per revolution: $Prev$ [pulse/rev]

Circumference of the drive roller: C [mm]

Under these definitions, the conveyor travel distance per encoder pulse, $\Delta Xenc$ [mm/pulse], is given by:

$$\Delta X_{enc} = \frac{C}{P_{rev}}$$

Let the distance between the camera imaging line (detection line) and the suction nozzle position be D [mm] in the conveyor coordinate system. If a foreign material detected at a certain time has a conveyor coordinate of $X=X_c$ at the time of detection, the conveyor coordinate at which the object passes directly beneath the nozzle is $X=X_c+D$.

Let the encoder count at the time of detection be E_{det} [pulse]. Then, the target encoder count corresponding to the instant at which the object passes directly beneath the nozzle, E_{noz}, is given by:

$$E_{noz} = E_{det} + \frac{D}{\Delta X_{enc}}$$

In the implementation, $\frac{D}{\Delta X_{enc}}$ is rounded to the nearest integer pulse count, thereby simplifying the comparison process performed by the PLC.

3.4 Calculation of the Nozzle Actuation Timing Considering System Delay

In the actual system, the following delay components exist between image acquisition by the camera and output of the nozzle actuation signal.

- Camera readout time and image transfer time: T_{cam}
- Processing time of the object detection algorithm: T_{det}
- Communication delay between the PC and the PLC: T_{com}
- PLC scan time and output update time: T_{plc}

The total system delay is therefore expressed as

$$T_{sys} = T_{cam} + T_{det} + T_{com} + T_{plc}$$

In practice, the total system delay, T_{sys}, is measured in advance, and the delay compensation distance ΔX_{sys} is calculated for each conveyor belt speed. These values are then set as PLC parameters so that the nozzle actuation timing is synchronized under various operating conditions.

3.5 Control Logic for Multiple Foreign Materials and Multiple Nozzles

To achieve high-throughput processing, the proposed system employs multiple suction nozzles arranged across the width of the conveyor belt, enabling simultaneous handling of multiple foreign materials.

(1) Definition of Nozzle Assignment Regions

The conveyor coordinate Y in the belt-width direction is divided into multiple assignment regions according to the number of nozzles. Each detected foreign material is assigned to the corresponding nozzle based on its Y-coordinate.

(2) Time-Sequence Control Using Queue Management

For each nozzle, the target encoder counts E_{trg} corresponding to foreign materials scheduled to pass beneath the nozzle are managed as a queue in chronological order. On the PLC, when the current encoder count reaches the value stored at the head of the queue, the corresponding nozzle is activated for a predetermined duration.

(3) Handling of Overlapping or Closely Spaced Suction Requests

If multiple suction requests are generated for the same nozzle within a short period, rapidly switching the solenoid valve ON and OFF is undesirable from the viewpoints of response time and mechanical service life. Therefore, the actuation time of the solenoid valve for a single suction request is defined as T_{on} [ms] in this system.

When the time interval between successive requests is less than T_{on}, the requests are merged into a single continuous pulse (continuous ON signal).

3.6 Generation of Nozzle Actuation Signals

The nozzle actuation signals are generated by comparing the current encoder count E_{now} with the target encoder count E_{trg} stored in the queue.

- An example of the ON condition for nozzle $j$is given by:

$$E_{trgj} - \Delta E_{pre} \leq E_{now} \leq E_{trgj} + \Delta E_{post}$$

Here, ΔE_{pre} and ΔE_{post} represent the allowable pulse tolerances determined by considering the nozzle response time and the effective suction range. When the current encoder count enters this range, the corresponding nozzle is turned ON and is turned OFF after the predetermined ON duration has elapsed. The ON duration was determined based on the nozzle opening diameter, suction flow rate, and conveyor belt speed so that sufficient suction time is ensured while the foreign material remains within the nozzle opening. Based on the evaluation results presented in Chapter 4 and subsequent chapters, the values of these parameters were optimized by evaluating the trade-off between improving detection sensitivity and reducing the rate of inadvertent removal of acceptable materials.

4. Development of the Foreign-Material Removal Unit

4.1 Design Requirements

Based on the foreign-material detection results and the nozzle control logic described in Chapters 2 and 3, respectively, the foreign-material removal unit is designed to remove foreign materials approximately 1 to 10 mm in size from bulk materials flowing on the belt conveyor by suction. The principal design requirements are summarized below.

- Target foreign materials:
  Small foreign materials approximately 1 to 10 mm in size, such as metal fragments, plastic fragments, and glass fragments, mixed with the bulk material.
- Target removal rate:
  At least 90% of the detected foreign materials.
- Yield rate (Acceptable Materials Retention Rate):
  The amount of bulk material not intended for removal (acceptable materials) that is inadvertently removed by suction shall be kept within an acceptable range relative to the total processing throughput.
- Operating conditions:
  Continuous operation shall be possible at the specified conveyor belt speed and throughput.
- Input/output specifications:
  The nozzle actuation timing (encoder pulse information) calculated in Chapter 3 shall be used as the input, and ON/OFF signals for each nozzle shall be output at the specified timing.

To satisfy these requirements, the foreign-material removal unit includes multiple suction nozzles, solenoid valves, a negative-pressure generation device (an ejector or a vacuum pump), and a dust collection unit.

4.2 Configuration

Figure 4-1 shows a schematic configuration of the foreign-material removal unit.

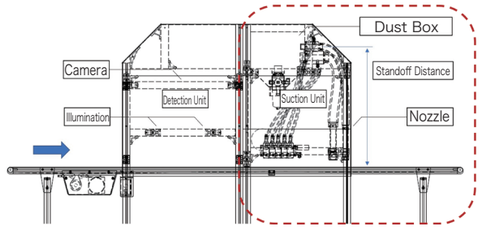


Figure 4-1 Overview of the Foreign-Material Removal Unit

- Multiple nozzles were arranged at equal intervals across the width of the belt conveyor, and each nozzle was assigned to a corresponding region in the belt-width direction.
- Each nozzle was connected to a solenoid valve through a short pipe, and a common negative-pressure manifold was placed upstream of the solenoid valves.
- The negative-pressure manifold was connected to an ejector or a vacuum pump. The pipe diameter and pipe length were determined to ensure sufficient suction flow rate and negative pressure in the vicinity of the nozzle opening.
- A dust box or a cyclone dust collector was arranged to collect the removed foreign materials along with a small amount of bulk material.

The nozzle tip was fixed so that its axis was approximately perpendicular to the belt surface. The distance between the nozzle opening and the belt surface (standoff) was set to several millimeters. This configuration localizes the suction region to the vicinity of the nozzle opening, thereby ensuring reliable capture of foreign materials while minimizing the removal of acceptable materials.

4.3 Specifications of the Suction Nozzle and Investigation of Suction Conditions

The foreign-material removal performance of the suction system depends on several parameters, including the nozzle diameter, standoff distance, negative pressure level, suction duration T_{on} and conveyor belt speed[7]. For the developed system, these specifications were investigated according to the following procedure.

(1) Nozzle Diameter and Standoff

Assuming a target foreign-material size of 1 to 10 mm, it was anticipated that, if the nozzle diameter was too small, the foreign material would be likely to become lodged in the nozzle opening, whereas, if the nozzle diameter was too large, the amount of acceptable materials removed by suction would increase. Therefore, comparative tests were conducted using several candidate nozzle diameters under the following conditions:

- Foreign material was placed directly beneath the nozzle with the conveyor belt stationary.
- The nozzle was actuated at a specified negative pressure and suction duration T_{on}, and it was confirmed whether the foreign material could be removed by suction.
- The amount of acceptable materials removed by suction was observed under several conditions with varying amounts of bulk material corresponding to acceptable materials.

(2) Negative Pressure Level and Suction Duration

In the proposed system, the foreign-material removal performance is adjusted by combining the negative pressure level during solenoid valve activation with the ON duration T_{on}. Increasing the negative pressure level and extending T_{on} generally improve the removal rate. However, they also increase the amount of acceptable materials removed by suction, thereby reducing the yield.

(3) Relationship with Conveyor Belt Speed

As the conveyor belt speed increases, the time during which the foreign material passes beneath the nozzle decreases. Therefore, the required suction duration T_{on} depends on the conveyor belt speed. In the present development, based on the timing design described in Chapter 3, the effective nozzle width and the corresponding passage time were calculated for each conveyor belt speed, and T_{on} was determined to cover the entire period during which the foreign material remained within the nozzle opening.

In the implementation, T_{on} is kept constant, while the allowable encoder pulse ranges ΔE_{pre} and ΔE_{post} are adjusted so that appropriate suction timing can be maintained even when the conveyor belt speed varies.

4.4 Evaluation of Removal Performance

This section outlines the evaluation results of the foreign-material removal unit alone. Detailed numerical results and comparisons under different operating conditions are presented together with the overall system evaluation in Chapter 5.

(1) Evaluation of an Individual Nozzle

First, the suction performance of an individual nozzle was evaluated by placing foreign material beneath the nozzle while the conveyor belt was stationary or operating at a low speed.

- Condition A: Foreign material was placed directly beneath the nozzle (near the center of the nozzle opening).
- Condition B: Foreign material was placed several millimeters from the edge of the nozzle opening.
- Condition C: The thickness of the bulk material corresponding to acceptable materials was increased so that the foreign material was partially embedded in the bulk material.

For each condition, the negative pressure level and the suction duration T_{on} were varied, and the foreign-material removal rate and the amount of acceptable materials removed by suction were recorded. The results confirmed that, for the prototype nozzle, there existed operating conditions under which the target removal rate could be achieved for Conditions A and B. It was also confirmed that, even when the foreign material was embedded in the bulk material as in Condition C, a certain level of removal performance could be achieved by appropriately setting T_{on} (see Chapter 5).

(2) Online Evaluation of Removal Performance

Next, the removal performance was evaluated with the

belt conveyor operated continuously under conditions close to actual operation while bulk material was supplied. In this test, the foreign-material detection and nozzle control logic developed in Chapter 3 were combined with the nozzle specifications and suction conditions determined in Chapter 4, and the percentage of detected foreign materials that were actually removed was measured.

Under the standard operating conditions simulating actual operation, it was confirmed that the target removal rate was achieved, assuming that the detection rate of the detection unit was 90% or higher. Quantitative measurements also confirmed that the amount of acceptable materials removed by suction was maintained within an acceptable range relative to the overall processing throughput (see Chapter 5).

These results demonstrate that the suction method and the nozzle specifications in the present development are effective for removing foreign materials approximately 1 to 10 mm in size from bulk material conveyed on a belt conveyor. Furthermore, it was demonstrated that, in combination with the detection and control algorithms described in Chapter 3, a system configuration that optimizes the trade-off among detection rate, removal rate, and the inadvertent removal of acceptable materials can be achieved.

5. Evaluation Tests

This chapter presents the evaluation tests conducted on the foreign-material detection unit and the suction removal unit described in the preceding chapters using an in-house simulated production line. The test procedures and evaluation results are also described below.

5.1 Test Materials and Setup

In this study, foreign materials approximately 1 to 10 mm in size mixed with bulk material conveyed on a belt conveyor were used as the evaluation target. Representative test materials used in the evaluation are shown in **Figures 5-1** and **5-2**.

- Bulk material: Vinyl pieces simulating recycled raw material
- Foreign material: Metal fragments, aluminum fragments, and granular soil



Figure 5-1 Bulk Material (Vinyl Pieces)

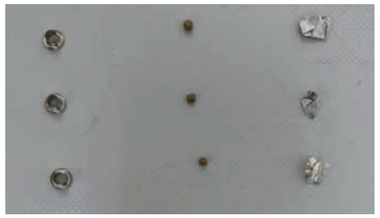


Figure 5-2 Foreign Materials (from left: Metal Fragment, Granular Soil, and Aluminum Fragment)

5.2 Offline Evaluation of the Foreign Material Detection Unit

5.2.1 Test Procedure

First, an offline evaluation of the foreign material detection unit was conducted using still images acquired while the conveyor belt was stationary. The evaluation focused on the effects of the following factors on the detection performance:

- Background (white belt / blue belt)
- Presence or absence of a polarizing filter

For each test condition, images containing a predetermined number of randomly placed foreign-material samples were acquired. Ground-truth data were then generated through an annotation process, and the detection rate and false detection rate were calculated. The results for each background color and polarizing-filter condition are summarized in **Table 5-1**.

5.2.2 Effects of Polarizing Filters on Halation and Glare

For the test conditions involving metal fragments and aluminum fragments, when no polarizing filter was used, halation and glare occurred on both the belt surface and the surfaces of the foreign material. As a result, the brightness of some foreign material became equal to or greater than that of the background, resulting in an

Table 5-1: Test Results (Offline Evaluation)

Target	Without Polarizing Filter		With Polarizing Filter			
	White Conveyor Belt		White Conveyor Belt		Blue Conveyor Belt	
	Detection Rate (%)	False Detection Rate (%)	Detection Rate (%)	False Detection Rate (%)	Detection Rate (%)	False Detection Rate (%)
Metal Fragment	93.3	13.3	100.0	0.0	93.3	0.0
Aluminum Fragment	100.0	16.7	100.0	6.3	80.0	36.8
Granular Soil	100.0	0.0	100.0	0.0	100.0	0.0

increased tendency for missed detections and false detections. In particular, depending on the angle of incidence of the illumination relative to the camera, the contours of the foreign material became saturated, resulting in unstable bounding-box localization.

In contrast, by installing polarizing filters on both the illumination and camera sides, halation and glare were decreased, thereby improving the brightness and color contrast between the foreign material and the background. As a result, the detection rate increased and the false detection rate decreased for the metal fragments (**Table 5-1**). For aluminum fragments, a reduction in the false detection rate was also observed. However, the influence of the background color was relatively greater, and under the blue-belt condition, both a decrease in the detection rate and an increase in the false detection rate were observed. This may be because sufficient contrast cannot be achieved for certain combinations of the representative color tones and reflective characteristics of the foreign materials and the background color.

These results indicate that, in the offline evaluation, the application of polarizing filters can decrease false detections caused by reflected light. Furthermore, the results demonstrate that the background color should be selected so as to provide sufficient contrast with the target foreign material.

5.3 Online Evaluation of the Foreign Material Detection Unit

5.3.1 Test Conditions

Next, an online evaluation was conducted while operating the conveyor belt and continuously supplying bulk materials. The evaluation was performed using the white-belt condition with polarizing filters, which exhibited the best overall detection performance in the offline evaluation described in Section 5.2. The following evaluation parameters were varied:

- Belt speed: Multiple conditions ranging from 9 to 20 m/min
- Exposure time: Values around the limit satisfying the "motion blur within one pixel" criterion described in Section 2.3

For each condition, the detection rate was calculated based on the number of foreign materials introduced into the bulk material during a fixed operating period and the detection results produced by the object detection algorithm. The results are summarized in **Table 5-2**.

5.3.2 Effects of Belt Speed and Exposure Time on Detection Rate

The online evaluation confirmed that the detection rate varied depending on the exposure time. When the exposure time was set too long, motion blur, in which the contours of the foreign materials were elongated in the

Table 5-2: Test Results (Online Evaluation)

Conveyor Belt Speed \ Exposure Time	500(μs)		1000(μs)		2500(μs)	
	Detection Rate (%)	False Detection Rate (%)	Detection Rate (%)	False Detection Rate (%)	Detection Rate (%)	False Detection Rate (%)
9(m/min)	83.3	0.0	98.3	1.6	95.0	6.6
14(m/min)	83.3	2.0	93.3	1.8	93.3	6.7
20(m/min)	81.7	3.9	93.3	1.8	95.0	8.1

conveyor travel direction, was observed under high belt-speed conditions. As a result, the bounding boxes of some foreign materials were estimated to be larger than their actual sizes, while others became merged with the background and were not detected, leading to a reduction in the detection rate. In addition, deformation of the foreign-material shape caused by motion blur tended to increase the false detection rate.

In contrast, when the exposure time was set too short, the captured images became darker, reducing the brightness contrast between the foreign materials and the background and consequently lowering the detection rate. Specifically, under conditions with shortened exposure times, when the illumination intensity and gain compensation were insufficient, the contours and texture information of the foreign materials became less distinguishable, resulting in an increased tendency for missed detections. Therefore, the exposure time under online operating conditions must achieve a balance between motion-blur reduction and maintaining sufficient image brightness (signal-to-noise ratio)[8].

The allowable motion-blur condition was defined, based on the relationship presented in Section 2.3, such that the image displacement in the conveyor travel direction during exposure did not exceed one pixel.

In this evaluation, the allowable exposure time calculated from the above relationship was used as the reference. Considering the image darkening caused by shortened exposure times, sufficient image brightness was maintained by increasing the illumination intensity and applying gain compensation. As a result, it was confirmed that appropriately setting the exposure time so that the motion blur remained within one pixel could reduce the decrease in detection rate caused by motion blur, whereas excessively shortening the exposure time resulted in darker images and consequently reduced the detection rate. These results indicate that, for online operation, the longest exposure time that satisfies the allowable motion-blur condition for the expected belt-speed range should be used as the default setting. When insufficient image brightness occurs, increasing the illumination intensity and/or applying gain compensation is effective for maintaining sufficient image brightness while preserving detection performance.

5.4 Evaluation of the Suction Removal Unit

This section presents the results of evaluating the effects of suction duration and nozzle diameter on the removal rate and yield rate of the suction-based removal unit.

5.4.1 Test Conditions

To evaluate the basic performance of the suction removal unit, the suction pressure was fixed at 0.4 MPa, while the nozzle diameter and suction duration were varied to measure the removal rate and yield rate. The experiments were conducted under the operating conditions that exhibited good detection performance in the online evaluation described in the previous section. Accordingly, the belt speed and exposure time were fixed at 9 m/min and 1000 μs, respectively. Two nozzle diameters, 10 mm and 20 mm, and three suction durations, 50 ms, 100 ms, and 200 ms, were evaluated.

In this evaluation, the removal rate was defined as the percentage of foreign materials successfully removed by suction, while the yield rate was defined as the percentage of acceptable materials remaining after the foreign materials had been removed.

5.4.2 Test Results

Table 5-3 summarizes the removal rate and yield rate obtained for each combination of suction duration and nozzle diameter.

Table 5-3: Removal Rate and Yield Rate for Different Suction Durations and Nozzle Diameters

Nozzle Diameter \ Suction Duration	50(ms)		100(ms)		200(ms)	
	Removal Rate (%)	Yield Rate (%)	Removal Rate (%)	Yield Rate (%)	Removal Rate (%)	Yield Rate (%)
ϕ 10 (mm)	75.0	89.7	100.0	87.4	100.0	84.7
ϕ 20 (mm)	60.0	69.3	100.0	60.8	95.0	49.3

5.4.3 Effects of Suction Duration and Nozzle Diameter on Removal Rate and Yield Rate

The results showed that the removal rate increased with increasing suction duration, whereas the yield rate tended to decrease. This is because a longer suction duration improves the probability of capturing foreign materials but also increases the likelihood of simultaneously removing the surrounding acceptable materials.

Furthermore, when the nozzle diameter was increased to 20 mm, the wider suction area resulted in a substantial reduction in the yield rate. In particular, under the 200 ms condition, the yield rate decreased to approximately 50%. Although the removal rate improved as the suction duration increased, the reduction in yield rate was more pronounced than that observed with the 10 mm nozzle.

These results indicate that, within the range of conditions evaluated in this study, the 10 mm nozzle provides a better balance between removal rate and yield rate. In particular, a suction duration of 100 ms achieved a 100% removal rate while maintaining the yield rate at an acceptable level, making it the optimal operating condition.

6. Discussion and Conclusions

This chapter discusses the conditions required for successful foreign-material detection and suction removal, as well as the key design considerations of the proposed system, based on the evaluation results presented in Chapter 5. Remaining issues and future work are also discussed.

6.1 Discussion on the Foreign-Material Detection Unit

(1) Guidelines for Mitigating Halation and Glare

The offline evaluation demonstrated that, for foreign materials with specular reflective surfaces, such as metal fragments and aluminum fragments, halation and glare became dominant under certain illumination conditions, resulting in an increase in both missed detections and false detections. The use of polarizing filters effectively decreased the reflected light component, thereby improving the contrast between the foreign materials and the background. This was experimentally confirmed to enhance the detection rate while reducing the false detection rate.

On the other hand, the detection performance was found to vary significantly depending on the combination of the background and the reflective characteristics and color of the foreign materials. For practical applications, it is therefore necessary to select a background color that provides high contrast with the target foreign materials while simultaneously decreasing brightness saturation caused by specular reflection and other optical effects.

(2) Trade-off Between Motion Blur and Dark Images

The online evaluation demonstrated that, under long exposure-time conditions, motion blur occurred at higher conveyor speeds, resulting in a decrease in the detection rate and an increase in the false detection rate. In contrast, shortening the exposure time effectively decreased the performance degradation caused by motion blur. However, when the exposure time was reduced excessively, the images became darker, and the resulting decrease in the signal-to-noise (S/N) ratio led to a reduction in the detection rate.

Therefore, during online operation, the exposure time should be set as long as possible while satisfying the criterion that the amount of motion blur remains within one pixel. Image brightness should then be maintained by increasing the illumination intensity and/or applying gain compensation. Furthermore, when the conveyor is operated over a wide range of speeds, stepwise switching of the exposure and illumination settings according to the conveyor speed (i.e., recipe-based parameter settings) is also an effective approach.

6.2 Discussion on the Suction Removal Unit

(1) Effect of Suction Duration

The evaluation results demonstrated that increasing the suction duration improved the removal rate but tended to reduce the yield rate. This is because a longer suction duration increases the likelihood that acceptable materials surrounding the foreign material will also be removed. Therefore, the suction duration should not be determined solely based on the removal rate but should instead be optimized using an overall performance index that also takes the yield rate into account.

(2) Effect of Nozzle Diameter

Increasing the nozzle diameter expanded the suction area, making it easier to improve the removal rate. However, it also resulted in a more pronounced reduction in the yield rate. Within the range of conditions

investigated in this study, the ϕ10 mm nozzle provided a higher yield rate than the ϕ20 mm nozzle, suggesting that it represents an effective choice in terms of balancing removal rate and yield rate.

For practical implementation, the system should be optimized by considering the particle-size distribution of the target material, its deposition state, and the number of nozzles (i.e., the width assigned to each nozzle). Accordingly, the design should be evaluated not in terms of nozzle diameter alone, but as a combination of nozzle diameter × assigned width × suction duration × negative pressure.

6.3 Design Guidelines for the Integrated Detection and Removal System

The findings obtained in this development are summarized below as design guidelines for the integrated foreign-material detection and removal system.

1.Reflection mitigation: Use polarizing filters and select an appropriate background color to reduce missed detections and false detections caused by specular reflection.

2.Motion-blur mitigation: Set the exposure time so that the amount of motion blur remains within one pixel at the operating conveyor speed and compensate for image darkening by increasing the illumination intensity and/or applying gain compensation.

3.Suction conditions: Optimize the combination of nozzle diameter and suction duration while considering the trade-off between the removal rate and the yield rate.

4.Control feasibility: For multiple-foreign-material, multiple-nozzle control, establish a rule for merging overlapping suction requests, and determine the operating conditions while taking into account the response limit and service life of the solenoid valves.

6.4 Future Work

1. Expansion of Target Foreign-Material and Bulk-Material Conditions

The present evaluation was conducted using representative foreign materials and bulk materials. However, it is necessary to verify the reproducibility of the proposed system under a wider range of conditions, including foreign materials with different material properties, colors, and shapes, as well as variations in particle-size distribution and deposited-layer thickness of the bulk materials. In particular, additional evaluations should be conducted for conditions in which foreign materials are buried within the bulk materials or the background texture is complex, since such conditions may degrade both the detection and removal performance.

2. Reliability Evaluation During Long-Term Continuous Operation

To achieve stable long-term operation of the system, reliability issues associated with prolonged operation should be investigated, including continuous operation of the solenoid valves, dust accumulation in the piping, nozzle clogging, and the stability of the negative-pressure source. In addition, design considerations should address maintenance intervals, ease of cleaning, and filter configuration.

3.Expansion of Evaluation Metrics

In addition to the conventional evaluation metrics, namely the detection rate, false detection rate, removal rate, and yield rate, it is necessary to establish a comprehensive evaluation framework that incorporates metrics such as the mass of acceptable materials lost relative to the foreign-material contamination rate, air consumption per unit throughput, recovery rate of unintentionally removed acceptable materials, and system responsiveness to variations in conveyor speed, in order to quantitatively demonstrate the benefits of implementing the system.

6.5 Summary

This paper reports an integrated design method in which the detection coordinates obtained by an object detection algorithm are converted into conveyor coordinates and encoder pulses, and suction nozzles are actuated while taking system delays into account. The evaluation results confirmed that reflection mitigation, using polarizing filters and appropriate background-color selection, and motion-blur mitigation, through exposure-time optimization, both contributed significantly to the detection performance. In addition, for suction removal, it was confirmed that an optimal combination of nozzle diameter and suction duration exists in terms of the trade-off between the removal rate and the yield rate. These results indicate that the proposed method is effective for detecting and removing small foreign materials from bulk materials on a belt conveyor.

Furthermore, the proposed method is expected to be applicable to various processes through the optimization of the imaging and suction conditions.

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AUTHOR



Shinya YASUDA

Joined in 2023

R&D Center, Technology Development Department, Development Section 3, DX Technology Unit