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Online synchronous inspection and system optimization of flexible food packaging bags by using machine vision and sensing technique

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ABSTRACT

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Flexible food packaging in the market is increasingly favored, and its quality is essential and indispensable for safety and convenience. However, quality inspection still stays in the manual stage, or partially manual inspection remains, in production, leading low efficiency, lack and even false inspection, hardly meeting the requirements of the modern output. This paper proposes and optimizes the design of an automatic detection system with intelligence for flexible food packaging bag, which can effectively be adopted to check the quality of packaging trademark patterns, fillers, and sealing quality. The inspection system runs with two-stage structure, machine vision, pressure sensing and synchronization to improve efficiency and ensure the normal production beat. Simplex Method is adopted to determine the best synchronous speeds online to achieve the best expectation. Comparison has been made between the manual inspection and our automatic operation, the sample of 10000 was statistically analyzed and results have shown that two workers were saved and the correctness rate of inspection raised up to 999.8‰.

INTRODUCTION

In the market, flexible packaging food is increasingly favored and widespread because of its relatively small space, convenient opening, and low manufacturing cost. Due to food safety and the economy, the requirements for flexible packaging food bags are higher. In addition to the printing quality and material property, more attention is paid to the bag material's strength, the trademarks' geometry, and sealing quality.

Quality inspection techniques of flexible packaging food bags mainly focus on: (1) pressure sensing inspection with "empty and air leakage"; (2) pattern recognition to judge "pattern defects"; (3) machine vision measures for "packaging quality" and so on. Koo et al. [1] inspected the heights of bumps on the flip chip substrate in a semiconductor package by using 3D inspection equipment. As a 3D inspection equipment, white light scanning interferometry with large FOV (Field of View) is used. Experimental 3D data repeatability test results for each substrate's flat bumps and round bumps are shown.

Wang et al. [2] worked out a theoretical integration system of the technological transformation of enterprises and products for new packaging production. Xing et al. [3] developed a reel-to-reel model for the improvement of product quality and efficiency of cigarettes by higher requirements with soft package trademark on holographic/concave as well as protruding lettering. To increase the quality and safety of the transparency of the products, Schneider and Franke [4] carried out a 100% inspection with process control of the whole production line, providing the framework for the total analysis through correction and refinement of the feedback variables. To overcome low efficiency and long time in labor-operated detection, Jie et al. [5] put forward an intelligent inspection system of dropper defects in up-hanging up line with by high-definition image acquisition and image defect recognition. Cantor, Stephen E. [6] developed a new type of UV-cured coating and almost-not-affected-by-fluorescent- agent adhesive. Such UV-cured coatings and adhesives can easily be observed by the naked eye with `black light' or by an online electro-optical device to improve the production quality. Wuneng et al. [7] worked out a novel way of power corridor visualization for UAV line detection information through data acquisition level image denoising, improving the detection accuracy of UAV line. Megalingam et al. [8] made up a virtual environment with a one-stop solution to test transmission-line checking robots with minimal or no additional cost. Based on the errors of displacement or rotation, Bedaka et al. [9] researched and provided position correction modeling for the object’s position and the robot’s pose. Such modelling contained an automatic hand–eye calibration and PnP algorithm calculating the object position error and compensating for the error on the production line.

Based on microwave imaging, Bellizzi et al. [10] revealed the foreign bodies may have contaminated the product in the transformation and packaging stages. Concerning a microwave system, novel imaging was created to build the image of the target. without reference sample. Sumanth et al. [11] showed an inspection robot consisting of several sensors, motors, and a camera to inspect the transmission line faults, with the Raspberry-pi control unit. Mazzetto et al. [12] worked out deep learning-based methodologies for visual inspection while leaving tiny footprints in the manufacturing environment and exploring it as an end-to-end tool to ease CVSs setup by four proofs of concept for a real automotive assembly line based on models for object, semantic segmentation, and anomaly detection. Sumagayan et al. [13] developed a new compensation method for centerline measurement of oil and gas pipeline with the mean of absolute position error reduction of 76.9%. Liu et al. [14] depicted the system's overall design ideas, functions, and processes with implementation methods for the real-time update of the whole process quality inspection data. Schneider and Franke [15]

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worked out a novel way of quality assurance for the whole production line by process control with optimal feedback variables.

Chen and Miao [16] developed an optimal detection method with classification to discriminate upper and lower feces-contaminated parts from skin. The feces-contaminated area was visualized with binary images by way of the principal component analysis and partial least square discriminant analysis. Zengin et al. [17] put forward and used sensor data of a power line inspection robot moving on the power line to measure the sag amount with an error of less than 2 percent. Jianxiong et al. [18] adopted 3D point cloud data by way of a PCL open project, providing a systematical analysis of the error types of laser line scanner and common error reducing solutions and calibration of the laser line scanner combined with a precision motorized stage. The proposed method ran with a higher precision and relative efficiency in real use. Xinyu et al. [19] created a method considering both spatial characteristic and sharpness evaluation, with YOLOv3 and ResNet, respectively, aggregating these two factors for high quality inspection images.

Yishuang et al. [20] contributed their effort in a new four-arm inspection robot. That could cross the strain tower with two different arm sets. Frantisek et al. [21] aimed at an optimal solution to problem of power transmission line inspection with a multi-route one-depot scenario. Integer Linear Programming obtained the optimal solution with the combinatorial metaheuristic. Via machine vision, Xingwei et al. [22] created a multiplex sensing method of complex mixtures, entitled TLC-SERS with experiments in better properties of selection and sensibility. Ke et al. [23] used machine vision to recognize the skirt module by creating three kinds of machine models of skirt contour, with image recognition for dress pattern drawing. To control the critical parameters in producing the integrated circuits, Dudkin et al. [24] proposed algorithms and software for solving problems arising from the microcircuit image analysis through machine vision and topology control equipment. Laszlo et al. [25] concentrate their work on preventing pharmaceutical waste from getting into the soil via telling incoming pills from different categories in terms of fractal. Roshchin [26] kept eye open the application in video surveillance for moving target by simulating human vision, computer functions, and the image acquisition device. Pengfei et al. [27] made an effort to move object monitoring and intelligent tracking measurement for video supervision with algorithms through formulas and comparison between the accuracy and success rate, and experiment. Xing et al. [28] researched and supplied a specific design method for the coalescence of two kinds of lenses with different features by optimizing operating distances and targeting surfaces, obeying rather strict requirements.

The current study uses "Machine vision + Sensing + logic algorithm + Optimal design" to check the quality of flexible packaging food bags, studies and optimizes the design of online dynamic inspection system for flexible packaging food bags, and realizes online dynamic synchronous inspection of trademark quality, filling, and sealing quality. The research gap is between the optimum inspection, supposed to be the synchronous online inspection with intelligence for every detail of all aspects necessary of the flexible bag, and the real situation that the production line runs with several workers for manual measurement combined with gauges for rather a simple checking such as numbering or weighing of the bags. This paper proposes to optimize the design of an automatic detection system with intelligence for flexible food packaging bags, which can effectively be adopted to check the quality of packaging trademark patterns, fillers, and sealing quality.

METHOD

1. Physical Property and Geometric Analysis of Flexible Food Packaging Bags

Common soft packaging food bag materials are multilayer composite materials containing plastic, with good hygiene, mechanical, barrier, moisture resistance, temperature resistance, odor resistance, and chemical stability. After forming the finished bag, it should have the integrity of the whole bag, beautiful geometric form, appropriate airtightness, and so on. The appearance and geometric morphology of flexible packaging food bags are shown in Figure 1 and Figure 2, respectively.

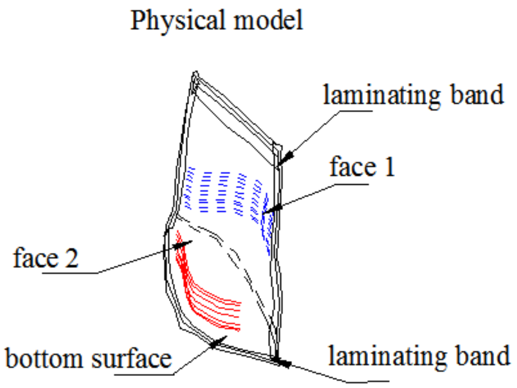

Figure 1. Outlook and contour of the soft bag

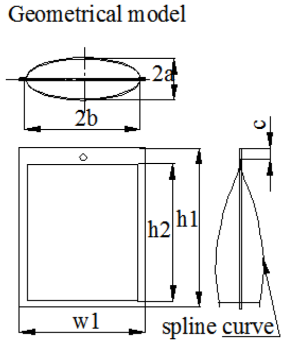

Figure 2. Geometrical model of the bag

2. Determination of Inspection Items and Indicators

According to the requirements of food safety, storage, and transportation as well as product aesthetics, the finished products of flexible packaged food bags should reach the standard and pass the inspection in the following five aspects, such as:

(1) Completeness of trademark and printing;
(2) the overall integrity of the packaging bag;
(3) Filling property of container;
(4) Opening sealing quality; and
(5) Comprehensive airtightness.

3. Methods and Algorithms

According to the above test content and the test method selected, the tests can be divided into three categories

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Category 1: integrity of trademark and printing, integrity of packaging bag (including aesthetics) —— use CCD camera to obtain the packaging bag pattern text information and packaging bag foreground information, and then through structural pattern recognition and color difference comparison to achieve inspection; Category 2: sealing quality and airtightness —— comprehensive use of machine vision and contact pressure sensing technology, screening sealing azimuth and including the sealing of the overall airtightness (the whole package on the prefabricated pores, the packaging bag is communicated with the atmosphere through the pores after packaging, except the finished package); Category 3: The integrity of the bag, filling —— using contact pressure sensing technology and norm algorithm.

4. Layout of the online synchronous inspection system

The inspection system is divided into four operation areas according to the above inspection items and inspection methods.

Region 1——Import zone: Starting from a section on the production line, the disordered, scattered, and unevenly distributed finished specimens of flexible packaging bags (hereinafter referred to as the specimens) form an orderly, uniformly distributed and uniformly oriented sequence of specimens through a special charging link and arrive at Region 2;

Region 2 —— the first detection-second resetting zone: According to the "six-point positioning principle", the complete positioning scheme is adopted to locate and clamp the specimen to realize the detection and subsequently return partial action in the second zone. Positioning and clamping should ensure the practical realization of the detection function on both sides of the specimen.

Region 3—— Second test - first resetting zone: The second zone specimen is sent to this zone to test the third side of the specimen using the accompanying principle

Region 4 —— leaving zone: After all specimen tests are completed, the specimen shall be sent to Zone 4. In this area, the specimens have been identified as "pass" or "fail" and located on or off the production line.

The overall layout of the detection system is shown in Figure 3.

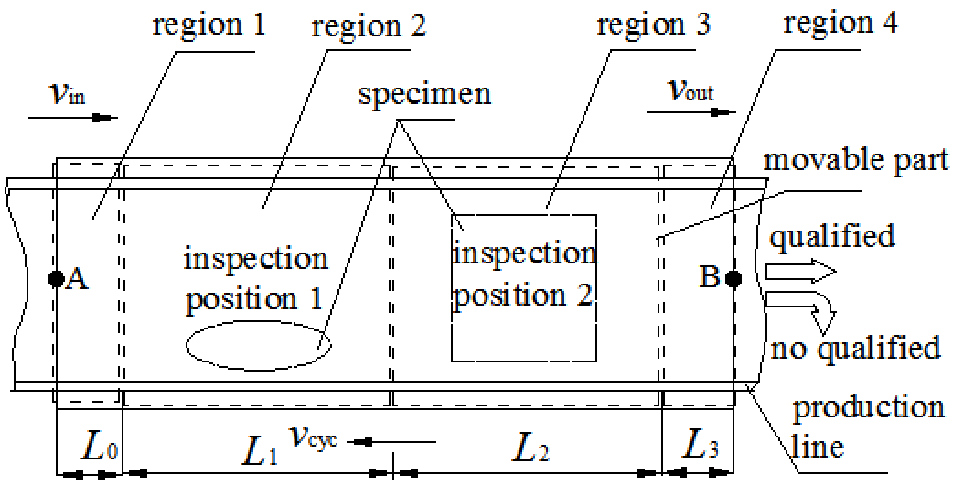

Figure 3. The general layout of the inspection system

RESULTS AND DISCUSSION

1. Production Line Operation Analysis

The production line of flexible packaging food bags should ensure a certain productivity under normal conditions. Considering the factors of equipment preheating, maintenance, and troubleshooting, the average speed (production beat) of the finished product is set as n/h, then the time of a finished product is shown in Eq. (1)

$$t_p = \frac{60}{N} (\min) \tag{1}$$

Therefore, the inspection link should be set on the production line, and the inspection time of a single finished product should be met as presented in Eq. (2)

$$t_{\text{ins}} \le t_p = \frac{60}{N} \tag{2}$$

2. Connection Between Online Synchronous Detection System and Production Line

If the test segment on the production line is L, all tests shall be completed from the start point A to the end point B. Therefore, to ensure effective detection, it is particularly important to shorten the detection time. Specimen coming into the first position in inspection from the production line is shown in Figure 4, while Figure 5 presents the inspection system with Figure 4. Specimen coming into the first position in inspection from production line machine vision.

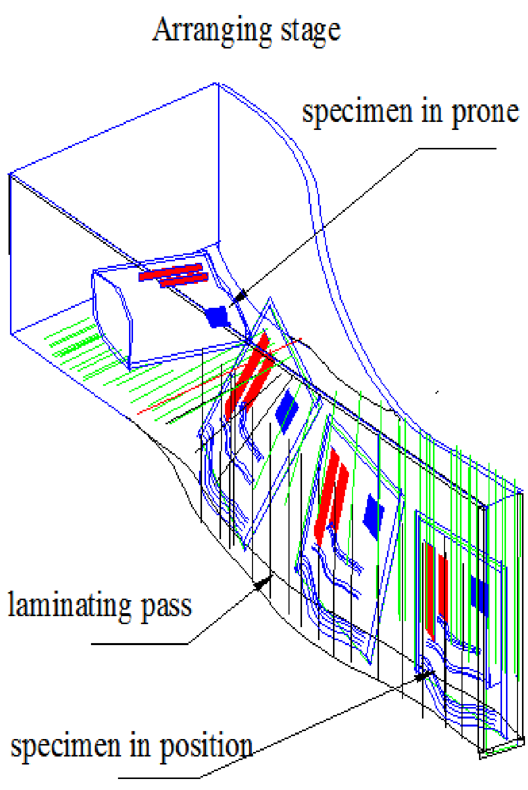

Figure 4. Specimen coming into the first position in inspection from the production line

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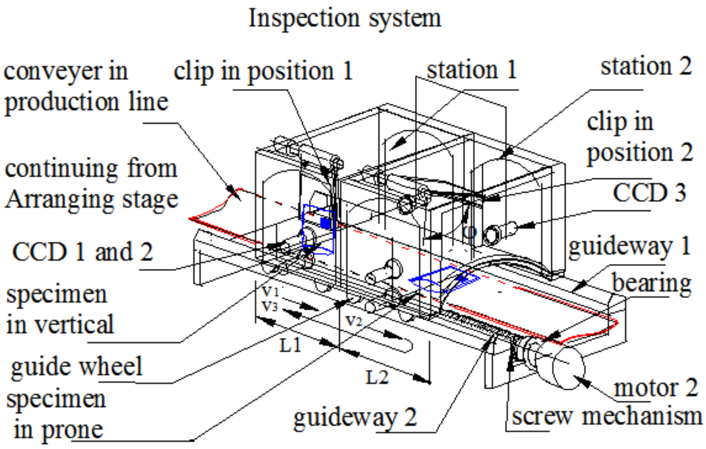

Figure 5. Inspection system with machine vision

3. Online Synchronization Inspection Method

To realize online detection, the detection system is directly integrated with the existing production line, and the import and export of the tested parts (flexible packaging finished food bags, hereinafter referred to as) are entirely connected with the production line.

In order to ensure the effective inspection of trademark patterns, machine vision is used for pattern recognition to screen the correctness of trademark pattern orientation. A so-called pattern-difference norm is utilized for checking the qualification of the package.

$$\left|P_{\mathrm{pr}} - P_{\mathrm{prs}}\right| \le \sigma \qquad (3)$$

where P_{pr} means the real pattern of the item in inspection, which may be expressed in matrix. Then, P_{prs} means the ideal or standard pattern of item used as the reference in matrix. Next, σ means a specific matrix with small values for all the elements. Detail of the pattern-difference norm will not be redundantly depicted here.

The CCD or CIMOS cameras were used to make the relative speed between the camera and the test piece zero to ensure the perceptual quality. Equation (3) is the container's filling property will be inspected using a pressure transducer.

Four pressure sensors are distributed and arranged in a diamond manner. To discriminate two situations, one is full of fillings, and the other is empty. A threshold value is prescribed, and the average value of four force components corresponding to four pressure transducers is adopted as shown in Figure 6.

$$F_{\mathrm{ins}} \ge F_{\mathrm{thr}} \qquad (4)$$

where F_{thr} means the threshold value of being full of fillings, coming out from statistic calculation based on test of big sample. F_{ins} means the effective value of pressure exerted on the flexible food bag by the following calculation.

$$F_{\mathrm{ins}} = \frac{1}{4}\sum_{i=1}^{4} F_i \qquad (5)$$

where F_i a pressure from the *i* - th pressure transducer. The transducer is employed with exerting force in terms of

$$F_{\mathrm{i}}(t)=F_{\mathrm{o}}\left[1-\exp\left(\frac{t}{T}\right)\right] \quad (6)$$

The detection system comprises a fixed part and a cyclic follower part. In the cyclic follow-up part, all detection items should be completed from point A to point B, simultaneously from the departure space to the export space, and then back to the departure space so as to complete A cyclic detection.

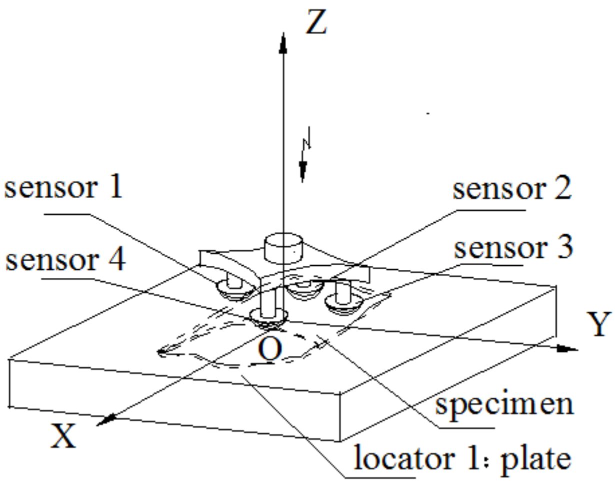

Figure 6. Filling property in inspection

Since three surfaces are to be tested on the specimen, and two surfaces can be tested simult aneously, two tests are required. In this process, the specimen needs two poses, so the detec tion working position must be designed. Set the speed of the cyclic follower part of station 1 a s v_1 and the leading speed as v_0; The speed of the cyclic follower part of station 2 is v_2, the le aving speed is v_3, and the resetting speed is v_4.

The above velocity cluster is denoted as

$$V=\{v_0,v_1,v_2,v_3,\ v_4\} \quad (7)$$

The time corresponding to the above speed respectively is shown in Eq. (8).

$$T=\{t_0,t_1,t_2,t_3,t_4\}=\{X_1,\ X_2,\ X_2,\ X_3,\ X_1\} \quad (8)$$

According to Eq. (2), we have

$$t_{\text{ins}}=\sum_{i=1}^{4}t_i\le t_{\mathrm{p}}=\frac{60}{N} \quad (9)$$

4. Optimal Design of Inspection System

The shortest inspection time (path) is the goal we pursue, and the physical and geome tric inspection requirements are adopted as constraints. Taking the basic action time of each i nspection as the decision variable, the optimal normalization of the inspection system as sho wn in Eq. 10. Figure 7 presents the moving cycle of the inspection system.

$$\begin{aligned}&\min f(X)\\&g_i(X)\le b_i\\&X\ge 0\\&t_1=t_2\ge 1.05s\end{aligned} \quad (10)$$

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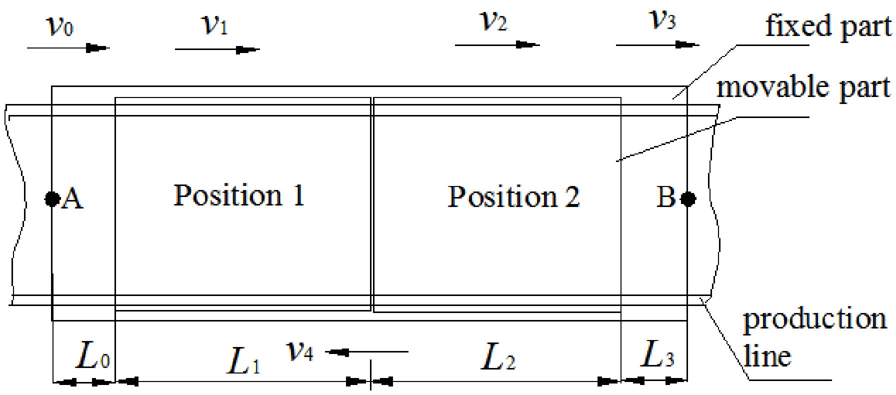

Figure 7. Moving cycle of the inspection system

Take N = 1000, then we have

$$t_p = \frac{60}{N} = \frac{3600}{N} = 3.6(s) \quad (11)$$

$$L_0 = L_3, \ L_1 = L_2; \quad v_0 = v_3, \ v_1 = v_2.$$

5. Movable Fixture Design

From the Principle of Six-point Location, the specimen is supposed to have a complete fixation to constrain all its degrees of freedom. On the other hand, the specimen is so soft that the locators should be to some extent, flexible accordingly. Then the solution for complete position is “a plat+a flexible double arcs”, as shown in Figure 8.

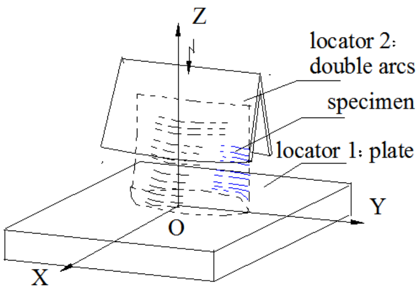

Figure 8. Complete position of the specimen

Location analysis:
Locator 1: rotations of X and Y, and linear movement of Z;
Locator 2: linear movements of X and Y, and rotation of Z.
Fixing and clamping:

Because of the geometry feature and the displacement of Locator 2, the double-arc part, plays a dual role in locating and clamping. Thanks for the angle of the double-arc part that exerts for movement of the part in Z direction, both clamping and locating functions of the specimen are realized. Figure 9 presents velocity field and distribution.

Design of the synchronic motion of the movable part:

With the screw gang, the movable part is driven to move from position 1 to position 2 and then return to the original position. Two convex triangular guideways are designed to support and guide the chassis.

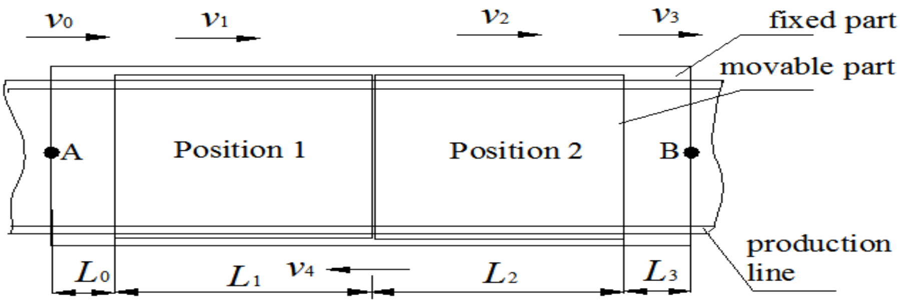

Figure 9. Velocity field and distribution

$$L_1 = W1 + \Delta. \tag{12}$$

$$L_2 = W1 + \Delta. \tag{13}$$

where W_1 means width of the specimen, and Δ is the margin of the space for the specimen to move and to check freely.

Respectively represent the speed of import and export, the speed of the first and second detection bit and the speed of cyclic reset. Then, the import and export processes, the first and second detection processes and the cyclic reset processes are respectively.

$$\begin{aligned} S_0 &= 2 \times v_0 \times X_1 \\ S_1 &= 2 \times v_1 \times X_2 \\ S_2 &= v_2 \times X_3 \end{aligned} \tag{14}$$

with

$$L_1 = L_2; \quad v_1 = v_2. \tag{15}$$

In order to ensure the production beat and detection quality, the time weight vector is taken

$$\begin{aligned} &\sum_{i=1}^{3} \alpha_i = 1 \\ &\alpha = \{\alpha_1, \ \alpha_2, \ \alpha_3\} = \{0.2, 0.5, 0.3\} \\ &2 \times X_1 + 2 \times X_2 + X_3 \le t_p \end{aligned} \tag{16}$$

The objective function can be written in matrix form as shown in Eq. (17).

$$\begin{aligned} &\min S = \alpha X^{\mathrm{T}} = \sum_{i=1}^{3} \alpha_i \times X_i \\ &X = \{X_1, \ X_2, \ X_3\} \end{aligned} \tag{17}$$

where α_i is the weight of the velocity component, take time as the decision variable, X_i is guide-in or leave-out time, X_2 is inspecting time in the first or second inspection position, X_3 is resetting time of the movable part of the inspection system.

The shortest inspection time should be taken as the evaluation function. Considering the convenience of expression, we take the three-stage detection time as the decision variable, and take the shortest distance formed at a certain speed as the objective function, which is equivalent to the shortest time. The constraint condition is shown in Eq. (10). In addition, Figure 10 presents the optimal design with complex method.

$$\begin{aligned} &X_1 \ge 0 \\ &X_2 \ge 0 \end{aligned} \tag{18}$$

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$$X_3 \geq 0$$

$$2 \times t_1 \times X_2 + t_2 \times X_3 \geq 2(L_1 + L_2)$$

$$v_1 X_1 = L_0$$

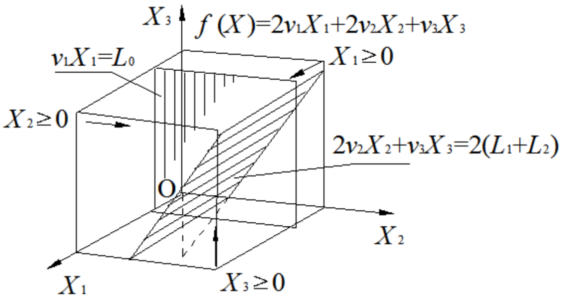

Figure 10. Optimal design with complex method

Result of the optimal system design is shown in Eq. (19)

$$T = \{t_0, t_1, t_2, t_3, t_4\} = \{X_1,\ X_2,\ X_2,\ X_3,\ X_1\} = \{0.36, 0.90, 0.90, 1.08, 0.36\} \tag{19}$$

6. Discussion

The difficulty of the inspection system contains the location and clamping of the specimen during inspection for the soft and flexible material of the bag; the methods selected to inspect both the geometric and graphical items on the specimen; realization of the inspection with the synchronous rhythm of production, if the speed difference between the CCD and the specimen is visible then the virtual picture may appear.

The current study has solved the above problems in three aspects: (1) make the inspection rhythm coincide that of the production line, and four regions were designed to meet the need of performance of entering-in, inspection in the first station, inspection in the second station, and leaving-out. All the actions realized within the required time, say 3.6 second in the case. (2) The naught-speed difference was taken as a point of the optimal design, so as the CCD may obtain as clear as possible pictures and characters for the use of pattern recognition of trademarks, as well as other images on the specimen. For this reason, two stations of the inspection system were designed and the movable parts carried the specimen and the CCD with the same velocity. (3) Simplex Method was selected to arrange the time spent within each function region, and optimal decision has been made for the inspection, see Eq. (17).

Comparison of the performances between the manual inspection and automatic inspection with our optimal system were made by statistics analysis of sample 10000. The production line ran with three workers for inspection, where two workers were on specific duty of the inspection of four contents of the bag by hand and eye, (1) completeness of trademark; (2) the overall integrity of the packaging bag; (3) filling property of container; (4) opening sealing quality; while another worker looked round for holographic supervision of the production line. With reinspection, mistakes or pseudo-inspection were found for 13 pieces. With the optimally-designed automatic system, keeping the productivity the same, six contents were detected including the character-picture printing property, and comprehensive airtightness beside the above four. Two workers were not needed and two bags were found with pseudo inspection. Some details of the research were listed in Table 1.

Table 1 Some inspection results of flexible food package bag online

Item content	Method	Result	Original production line status	Comment
trademark	pattern-recognition+algorithm	automatic+in-telligent+√*	manual+×**	reliable
integrity	three-D press sensing+algorithm	100% automatic check	manual spot check+×	quality ensured
container filling	nine point pressing sensor array+algorithm	100% automatic and intelligent check+◎***	manual spot check+×	acceptable; to improve
opening seal	machine vision+pattern-recognition+ algorithm	100% automatic and intelligent check+√	manual spot check+×	reliable
character-picture	machine vision+difference norm algorithm	100% automatic and intelligent check+√	manual spot check with eye+√	complicated techniques used
airtightness	two-D sensing+algorithm	100% automatic and intelligent check+√	no check	reliable

Note:*√——excellent;**×——no good;***◎——mediocre， in performance

CONCLUSION

Based on the analysis of the physical properties and quality inspection requirements of general food flexible packaging bags, the three problems of geometry and orientation, pattern and color difference, content and airtightness were summarized, and the online synchronous food flexible packaging bag quality inspection system was proposed and optimized.
By coalescence of machine vision and logic algorithm to determine the correctness of the trademarks of food flexible packaging bag, the contact pressure sensing technology was used to detect physical damage, airtightness, and retention. Using the simplex method, an optimized online synchronous inspection system was designed with the shortest time (path) as the evaluation function, the three-stage velocities as the decision variables, and production rhythm and path as the constraints.

For the synchronous working rhythm with the present production line, the tooling of input, positioning, output, and return to the production line were considerately designed to realize the "seamless integration" between the detection system and the production line. Taking an enterprise product as an example, the investigation was done by statistics analysis with a sample of 10000. Results have shown that the automatic inspection system designed optimally could meet the requirements of online synchronous and intelligent detection to boost the production line of high efficiency by 1.1‰ in correctness rate, two more inspection contents, and two workers saved.

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