Design and Research of High-throughput Automation System for Food Testing Laboratory

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Abstract In the process of food testing, human operation is an important variable affecting the experimental results. In order to reasonably avoid the influence of human subjective operation behavior on the accuracy of detection results, the laboratory information management system was used as the information platform to design a high-throughput laboratory automation pre-treatment system based on the deep integration of mechanical principles, visual analysis, high-speed conduction, intelligent storage and other technical systems. The experimental results showed that the system could shorten the sample circulation cycle, effectively improve the laboratory biosafety, and meet the requirements of high-throughput processing of samples.

Key words Food testing; Automation; Pre-treatment system; High throughput

Food testing results are professional indicators that directly reflect the quality and safety of food. Whether it is food sensory indicators, nutritional elements, flavor components, or pollutant factors, the determination of the final product content needs to rely on food testing technology[1]. Samples are the main object of food testing, and the entire process of sample inspection and testing is a transitioning process from harmful environment to harmless environment. The tested samples cover over a hundred food varieties in 33 major categories[2], involving various forms of objects such as liquid, semi solid, solid, and powder. Due to the differences in the properties and testing items of testing samples[3], the storage environment and time requirements are different, and the degree of their disposal rationalization will directly affect the effectiveness of the testing results[4].

The high-throughput automation system for food testing laboratories starts with a pre-treatment system and is an important component connecting sampling and testing processes. The sample pre-treatment in conventional food testing laboratories is mainly conducted through manual work. Due to the lack of strict quality control standards, there are problems such as poor sample handover and long circulation time[5], especially when dealing with sudden major food safety accidents, it is difficult to meet the needs of high-throughput testing in the laboratory. In response to the above issues, a laboratory information management system is designed as an information platform, so as to achieve sample pretreatment in food testing laboratories for different sample attributes and testing requirements based on deep integration of technical systems such as mechanical principles, visual analysis, high-speed transmission, and intelligent storage[6].

Design Concept of High-throughput Automation System for Food Testing Laboratory

Complete flow scheme of food testing automation system

The high-throughput automation system for food testing laboratories is built on the basis of existing efficient and high-precision food testing laboratories, with the aim of achieving food safety and quality testing. It optimizes the integration of various analytical instruments with experimental prep-treatment, sample preparation, and data analysis units in the laboratory, and adopts different algorithm models or calculation strategies suitable for various scenarios to achieve the efficient analysis and detection system that seamlessly integrates automation systems with laboratory information management systems (LIMS). For different forms of samples in the current food testing process, the food testing automation system should strictly follow the requirements of national and industry standards, and establish a fully mechanical and automated sample pre-treatment operation procedure based on artificial intelligence. It can automatically establish a sequence table according to different detection tasks, run the sequence to complete data processing, obtain analysis results, and perform online secondary detection for non parallel and over-standard samples. Moreover, it is also equipped with the ability to quickly handle major emergency testing tasks, which can ultimately achieve food safety risk warning, providing technical basis for government scientific supervision.

Theoretical framework of food testing automation system

The high-throughput automation system for food testing laboratories should be an organic whole that covers precise management modules, efficient mechanical units, and rigorous system standards.

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The "three-control" laboratory automation system model is built inside the management system based on sample control, detection control and data management, which organically integrate the management model into the whole process before, during and after detection. The connection of various testing and analysis platforms makes it possible to optimize and manage sample data to effectively shorten sample turnover time.

The mechanical unit runs through the entire process of the food testing laboratory. The various equipment such as robotic arms and high-speed circulation machinery forms the "three-dimensional" mechanical system composed of independent domain system, branch comprehensive system, and linear structure system based on different testing methods and connecting instruments in each stage of the detection process. In the face of different testing samples and different testing projects, different experimental equipment and testing instruments can be applied to complete high-throughput detection of the system based on the automatically established sequence table.

The "three standards" framework, composed of standardization of experimental methods, instrument interfaces, and testing equipment, forms a standardized system consisting of experimental names, experimental methods, instrument interfaces, testing equipment, and barcode identification, which achieves the dynamic integration of sample pre-treatment with testing equipment, mechanical structure, data analysis, and sample post-pretreatment.

Design of High-throughput Sample Pretreatment System in Food Testing Laboratory

The sample high-throughput pre-treatment system consists of sample interaction unit that conduct transition from an external environment to a harmless environment, as well as sample sorting unit, high-speed transmission unit, sample storage unit, sample transfer parts, and central control unit, all of which are defined as environmentally friendly work areas. The overall architecture is shown in Fig. 1.

Design principle of sample interaction unit

The sample interaction unit is composed of sample interaction belt conveyors, self opening and closing doors, a binocular camera, a light source, and a sample terminal. During operation, the inspection personnel place the empty preset box on the initial end of the sample interaction belt conveyor. The original sample image during the process of placing the sample in the preset box is synchronously collected through dual perspectives, and the convolutional neural network is used to train the sample set to identify the sample submission information and initial state, and determine the contamination of the sample. At the same time, the sample terminal scans the barcode information on the preset box, updates the barcode information data through the laboratory information management system, and establishes a corresponding relationship between the preset box and its internal sample status.

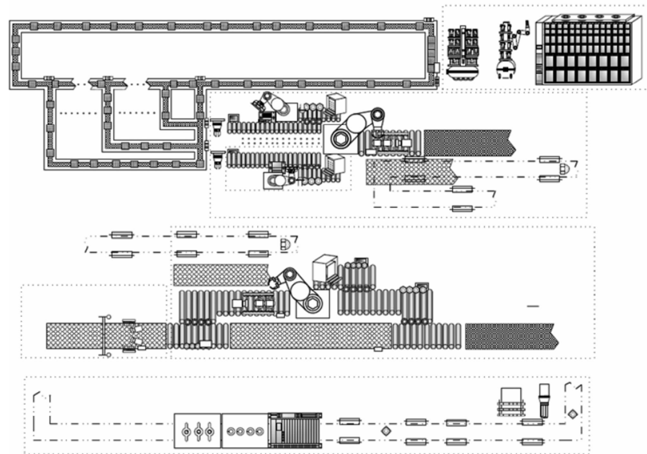

Fig. 1 Overall architecture of the high-throughput sample pre-treatment system in food testing laboratory

Design principle of sample sorting unit

The sample sorting unit consists of a mixed sample loading operation manipulator and an independent sample sorting manipulator. The structure of the independent sample sorting manipulator is the same as that of the mixed sample loading operation manipulator, including a six axis robot arm, a self suction robotic gripper, a backup gripper, a disassembly part, an assembly part, a backup gripper conveying device, a pneumatic device, an electronic control unit, and a basic base. The structure is shown in Fig. 2.

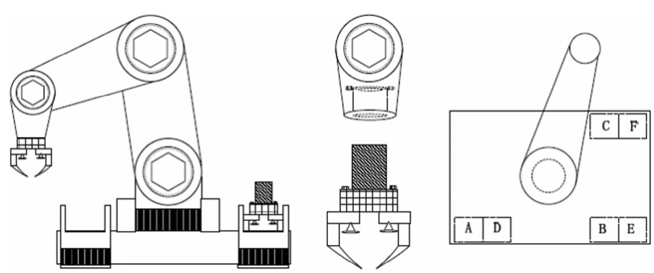

Fig. 2 Structure of the robotic arm for sample sorting operation

During the operation, when collecting the real-time image data of the operation area, the robotic arm performs a forward rotation on each individual sample, and a rotation cycle of the individual sample is defined as a time series. A mixed Gaussian background model is designed to extract the foreground image of the individual sample, and convolutional neural networks are applied to train the image data in the sample foreground image dataset to identify the contamination of the outer packaging of the individual sample, and conduct spatial pose detection on individual samples. To avoid contamination of the robotic arm by pollutants, after placing the contaminated samples in the contaminated sample transferring part, the robotic arm positions the disassembly part, automatically completes the gripper change, and restores the operation status. The self suction robotic gripper is transported from the push device to the robotic gripper collection part, and the spare gripper is moved to the assembly slot.

Design principle of sample storage unit

The sample storage unit consists of an AGV transfer robot and a multi-stage sample storage unit. The AGV transfer robot is used to store the sample storage boxes on the sample high-throughput transmission unit into the multi-stage sample storage unit. The AGV transfer robot includes a mechanical unit, a control unit, and a power unit. The mechanical unit includes a gripping part, a sensing part, and a walking part. The gripping part includes a six axis stacking robotic arm, an end gripping part, and a loading platform. The sensing part includes a laser sensor group and a visual system. The walking mechanism includes an AGV body, a moving device, and a turning device, and the body can move and rotate in any direction, without being limited by the shape of the body itself. The control unit is built into the AGV body, including an information transmission device, data processor, and driving device. The power unit is built into the walking part, including the walking motor and battery pack. The information transmission device of the AGV transfer robot uses the AGV body as a mobile terminal, and builds a scheduling mechanism working network including routing and coordination terminals to coordinate the path navigation and sample information transmission of multiple AGV transfer robots.

Research on Fetching Strategies for Visual Perception System

Design principle of perception algorithms

The binocular camera in the sample sorting unit collects images of mixed samples in the preset box in the operation area, and a 3D reconstruction algorithm is designed for the mixed sample images in the preset box. Under the condition of meeting the epipolar constraint theory of binocular vision, the images are performed with epipolar rectification, and a feature matching strategy based on Harris corner detection is designed, as shown in formula 1:

$$\begin{cases} M(x, y) = \sum_{\omega} \begin{bmatrix} I_x \\ I_y \end{bmatrix} [I_x, I_y] = \omega \otimes \begin{bmatrix} I_x^2 & I_x I_y \\ I_x I_y & I_y^2 \end{bmatrix} \\ R(M) = \det(M) - k trace^2(M) \end{cases} \quad (1)$$

After completing feature matching, a region matching algorithm based on disparity gradient constraint is designed for non feature point images to complete the 3D reconstruction of the mixed sample images in the preset box, as shown in formula 2:

$$\begin{cases} d_p = p_r - p_l = (\mu_{prx} - \mu_{plx}, v_{pry} - v_{ply}) \\ d_q = q_r - q_l = (\mu_{qrx} - \mu_{qlx}, v_{qry} - v_{qly}) \\ \nabla d = \dfrac{|d_p - d_q|}{|d_{cs}(p_m, q_m)|} \end{cases} \quad (2)$$

A spatial coordinate algorithm based on distance measurement by subtense method is designed for the 3D reconstruction model of mixed sample images, obtaining the spatial point position coordinates and point cloud data of each individual sample, which are used to control the robotic arm to grasp each individual sample in the mixed sample.

Sample pre-treatment system testing

As is shown in Table 1, the high-throughput sample pre-treatment system for food testing laboratory effectively avoids the effects of subjective behavior of human factors on the testing samples, simplifies and optimizes the workflow. Although the non-destructive sample recognition rate is 2.6% lower than that of manual operations, the sample processing volume increases, the turnover time shortens, and the number of manpower decreases. As the number of image samples increases, the recognition rate of contaminated samples will further improve.

Table 1 Testing comparison results

Testing comparison	Manual operation	Automation system
Number of daily samples	300 – 500	700 – 1 200
Number of operators	10	3
Sample circulation time//h	6.5	1.2
Sample testing items	55	55
Identification rate of stained samples//%	97.9	95.3

Conclusion

The pre-treatment system meets the general adaptability requirements of food testing laboratories for samples, covering over a hundred types of food in 31 major categories, involving various object forms such as liquid, semi solid, solid, and powder. The system design objectively and reasonably divides harmful and harmless working environments. The sample circulation process strictly ensures sterile operation, effectively avoiding external pollution sources during the sorting and storage process of samples. The system effectively avoids the impact of subjective behavior caused by human factors on sample testing, simplifies and optimizes workflow, shortens sample turnover time, saves human resources, improves laboratory biosafety, and meets the requirements of high-throughput sample sorting.

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