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Research Article

Research on Intelligent Production Line Design and Dynamic Balance for 3C Products

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An intelligent production line design scheme for 3C products is introduced amid the current situation of low automation in assembly, testing, packaging and other production contacts in the 3C manufacturing industry, high demand for upgrades and fierce market competition, taking a 3C electronic product as an example to investigate its overall layout, workstation structure, architecture system and control system. In addition, according to the concept of lean production, a method is proposed to realize dynamic balance of production line. First of all, the dynamic balance mathematical model is established, then the genetic algorithm is used to solve the model parameters, and finally the production line can keep the balance by adjusting the running speed of field equipment according to the calculation results. The actual verification shows that the production line runs stably, completes the automatic and intelligent production of products, with a balance rate at an excellent level. This can serve as a reference for relevant enterprises to build intelligent production lines for 3C products and implement lean production.

1. Introduction

As China's economy has shifted from the stage of high-speed growth to the stage of high-quality development, higher requirements have been put forward for the high-quality development of the manufacturing industry, which constitutes the foundation, tool and basis of national development [1]. In the manufacturing field, 3C products account for a large share. According to public data, the 3C manufacturing leader that is China ranks first in the world, accounting more than 70% of global production. "3C product" is the umbrella term for Computer, Communication and Consumer Electronics [2]. Such products are small in size, huge in quantity of parts, and highly complex to process. The whole process can be divided into three parts: upstream parts processing, midstream module packaging, and downstream machine assembly, testing and packaging. At present, the upstream and midstream links of the 3C industry chain have a relatively high degree of automation, while the downstream links are still dominated by manual labor. With the weakening of the demographic dividend and rising labor costs, enterprises have an urgent need for product assembly, testing and packaging automation, which has become the focus of scientific and technological workers in related fields.

Researchers such as Chen Danhui [3], Wu Zhipeng [4] and Su Jian [5] designed product inspection or assembly workstations based on industrial robots, which solved the problem of automated operation of a single process step but did not involve the overall solution of the complete production process of the product. Chen Fang [6], Hu Panfeng [7], Chen Qiong [8], Lu Ye [9] et al. built a multi-unit automatic production line with PLC as the control core to realize the automation of the whole production process of 3C products, from the unloading of parts to the warehousing of finished products. However, the key issues affecting the work efficiency and economic benefits of the production line, such as load distribution and balance rate among units, are not considered. In view of this, this paper takes a 3C electronic product as the research object, refers to the concept and technology of intelligent manufacturing, starts from the aspects of production line layout, workstation structure, architecture system and control system, and designs an intelligent production line that can complete the entire production process of the product, and on the basis of this

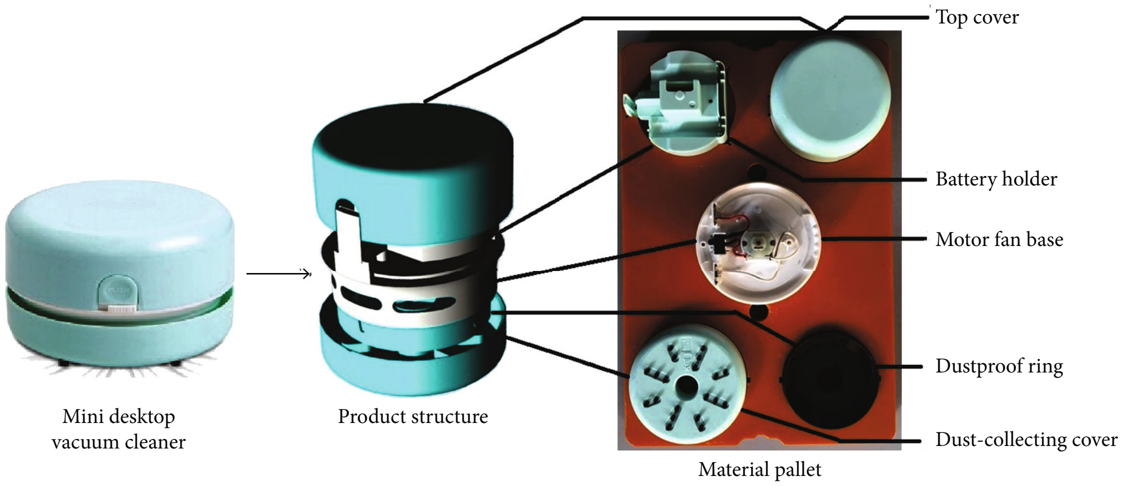

Figure 1: "Mini Desktop Vacuum Cleaner" of 3C Products.

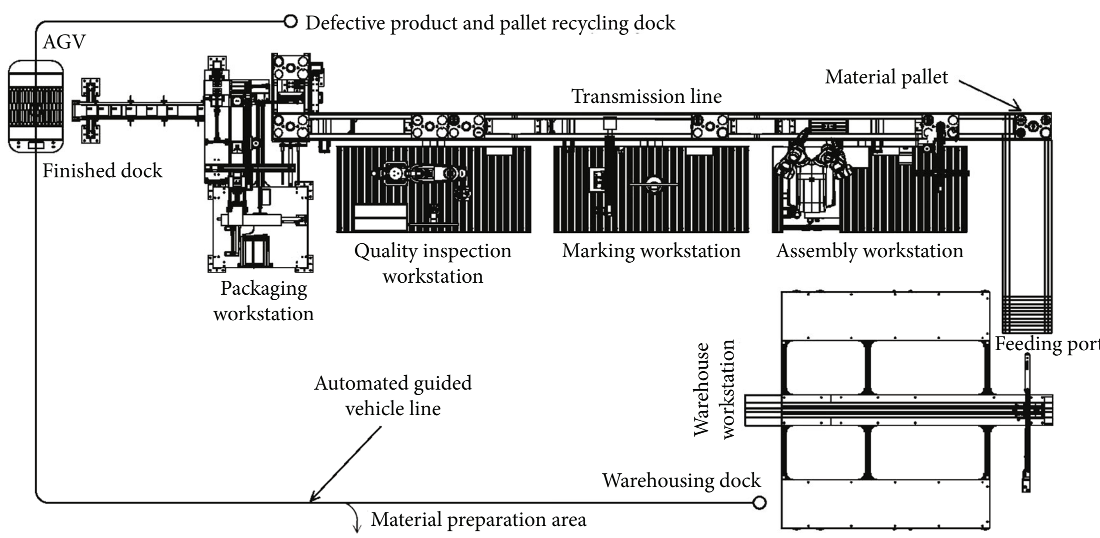

Figure 2: The overall layout of the production line.

production line, a dynamic balance scheme is researched and implemented to provide a feasible technical means for the realization of lean production.

2. Production Objects and Overall Layout Design

As shown in Figure 1, the "mini desktop vacuum cleaner" can absorb dust and residues and easily clean the desktop, keyboard, sofa, etc. It is a typical consumer electronic product. The product consists of five parts, including motor fan base, battery holder, dustproof ring, dust-collecting cover and top cover. The main production process includes parts assembly, brand LOGO printing, quality inspection and packaging. To ensure product quality, improve production efficiency and reduce costs, the product production line is designed according to the "one-line multi-station" model, and the product components are placed as raw materials on a specially customized material pallet (there are 5 component positioning grooves on the front, and the bottom is inlaid with RFID electronic tags), and transported to various workstations through pallets for production operations.

The overall layout of the production line is shown in Figure 2, including warehouse workstation, assembly workstation, marking workstation, quality inspection workstation, packaging workstation and conveying workstation. The warehousing workstation is responsible for the delivery of raw materials and the warehousing of finished products; the assembly workstation is used to assemble the motor fan base, battery holder, dustproof ring and dust-collecting cover; the marking workstation is for marking the brand LOGO and customized words on the top cover; the quality inspection workstation is for the function, appearance inspection and top cover assembly, the packaging workstation is for packaging products into finished products, and the conveying workstation is responsible for the

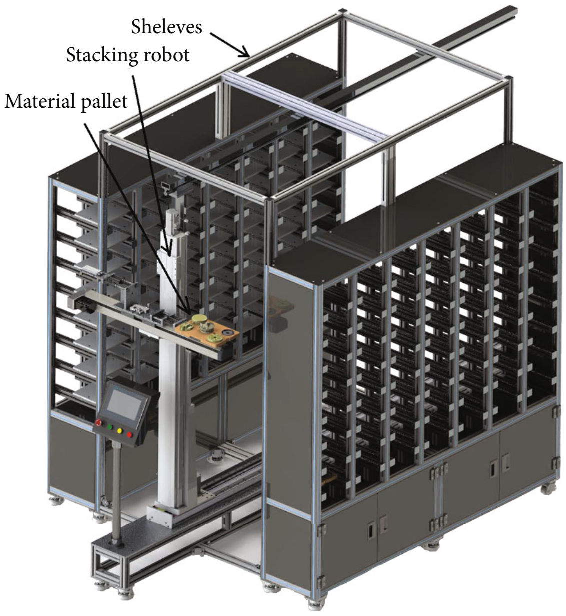

Figure 3: Warehouse workstation.

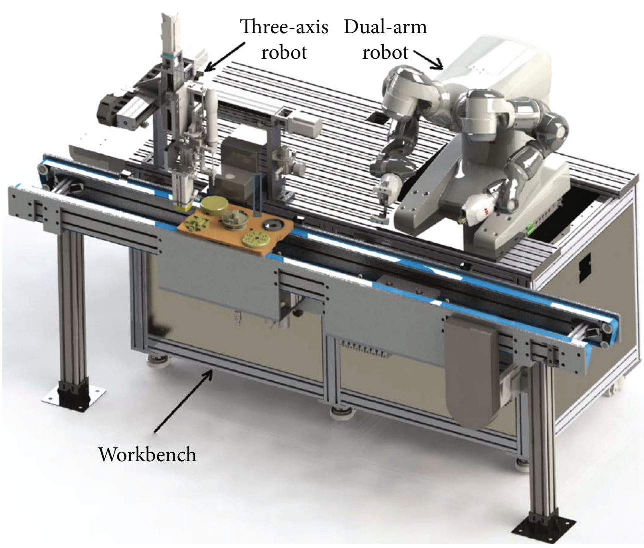

Figure 4: Assembly workstation.

transportation of material pallets and finished products, while integrates many intelligent manufacturing technology elements to achieve intelligent production.

3. Workstation Structure and Process Design

3.1. Warehousing Workstation. The mechanical structure of the warehousing workstation is shown in Figure 3. The function is to realize the warehouse of raw materials and finished products and automatic out/in to the warehouse. It is mainly consisted of stacking robots and shelves. The stacking robot is the implementation mechanism of the three-dimensional warehouse, which consists of X axis, which controls the horizontal walking, Z axis, which controls the vertical lifting, and Y axis, which controls the telescopic fork. The X/Y/Z axes are all driven by servo motors, and their motion control is realized by driving 3 servo drivers through pulse and direction signals output by PLC, and limit protection is carried out by using travel switches. The shelves are made of aluminum profiles, with 1 designed roadway, and 112 warehouses are arranged in 2 rows, 8 layers and 7 columns. Each warehouse is equipped with an induction sensor to detect the status of the warehouse. When the workstation is running, the pallets loaded with raw materials are released from the right shelf in the order from left to right and bottom to top; The finished products are put into the warehouse from the left shelf in the order from right to left and bottom to top.

3.2. Assembly Workstation. The mechanical structure of the assembly workstation is shown in Figure 4. The function is to complete the assembly of the motor fan base, battery holder, dustproof ring and dust-collecting cover. It mainly consists a workbench, a three-axis robot and a YUMI dual-arm robot. The size of the workbench is 1400 mm (length) $*$ 660 mm (width) $*$ 750 mm (height), and it is divided into upper and lower layers to provide the installation basis for the station equipment. The X and Y axes of the three-axis robot are driven by stepper motors, and the Z axis is driven by servo motors. YUMI is a dual-arm 14-axis collaborative robot launched by ABB. It is lightweight, easy to install and use, and its multi-functional dual-arm can realize multi-task parallel processing. It is a “sharp tool” for the assembly of small 3C products. The two robots cooperate with each other to complete product assembly in a sequential collaborative manner. When the workstation is running, the material pallet first comes to the front of the three-axis robot. The robot picks up the battery holder through the pneumatic clamp and places it on the motor fan base and knocks them down from the top to make them snap together and fasten. After that, the automatic screw-driving machine which fixed on the z-axis of the robot puts the screws into the screw holes on both sides of the battery holder and fastens them to form assembly 1. Then the pallet comes to the front of the YUMI robot, YUMI picks up the assembly 1 with one hand, and the other hand picks up the dustproof ring, dust-collecting cover successively, snap and fasten them to the assembly 1. Through the cooperation of the two arms, the anthropomorphic action completes the assembly, forming the assembly 2 [10].

3.3. Marking Workstation. The mechanical structure of the marking workstation is shown in Figure 5. The function is to mark the brand LOGO and customized words on the top cover of the product through a high-power laser, which is mainly consists of a workbench, an industrial computer and a laser marking machine. The workbench is the same as the assembly workstation and will not be reintroduced here (the same below). EzCad2, a professional marking software, is running on the industrial control computer. The brand LOGO pattern is edited and fixed in the software in advance. The customized words are obtained by extracting the data information in the RFID electronic label. Both of

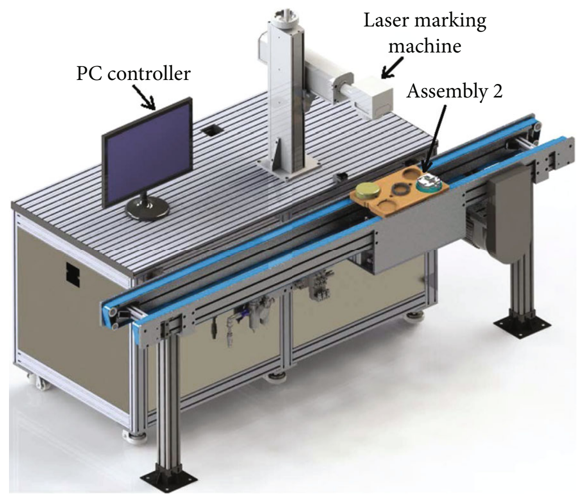

Figure 5: Marking workstation.

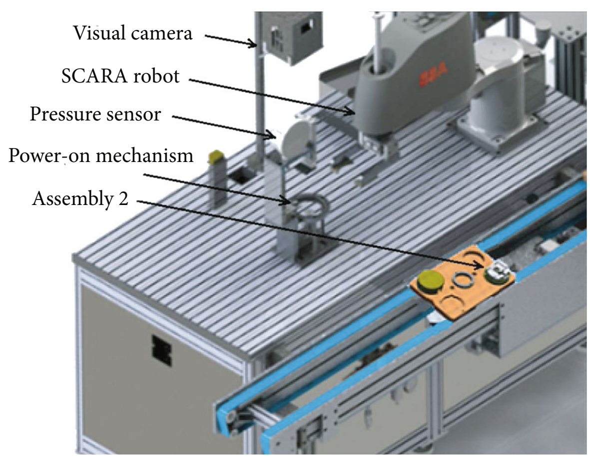

Figure 6: Quality inspection workstation.

the brand LOGO and customized words are transmitted to the marking machine through the RS232 interface. The marking machine adopts fiber laser marking machine, and air cooling. During the operation of workstation, when the material pallet arrives at the station, the marking machine marks the brand LOGO and customized words on the top cover of the product.

3.4. Quality Inspection Workstation. The mechanical structure of the quality inspection workstation is shown in Figure 6. Its function is to test suction and visually detect screw of assembly 2, as well as the top cover pattern. It mainly consists worktable, SCARA robot, function detection device and machine vision camera. The SCARA machine adopts ABB's IRB 910SC 4-axis horizontal multi-joint robot, which is fast and cost-effective, and can be used in a narrow space. It is an ideal choice for small 3C product sorting, handling and parts inspection. The function detection device consists of a power-on mechanism and a digital pressure sensor, wherein the positive and negative probes of the power-on mechanism can be inserted into the battery compartment of the assembly 2 to supply power to the motor. The machine vision adopts the In-Sight series 7401 smart camera of Cognex and its integrated PatMax pattern tool can be easily applied to various task scenarios of pattern matching or recognition. When the workstation is running, the material pallet stops before it reaches the SCARA robot. The robot first picks up the assembly 2 and sends it to the functional testing device to power on, so that the motor drives the internal runner to rotate. At the same time, the pressure sensor detects whether the negative pressure suction is up to standard. Then, assembly 2 is sent to the visual camera for screw detection and put back to the original position of the pallet after completion; Finally, the robot picks up the top cover and sends it to the visual camera for LOGO detection. If the above tests are all qualified, the robot places the top cover on the assembly 2 and knocks down from right above to make them snap and fasten to complete the final assembly, forming a semi-finished product. If the above detection is unqualified, the robot will put the top cover back to the original position of the pallet, and the pallet will be transferred to the defective product dock after this station to go offline.

3.5. Packaging Workstation. The mechanical structure of the packaging workstation is shown in Figure 7. The function is to put semi-finished products into packaging boxes, package them into finished products, and then transport them to the finished product dock. The main equipment includes three-axis robots, box sealing equipment and finished product dock. The box sealing equipment consists of a series of solenoid valves, guide plates and cylinders. The solenoid valves control the cylinders to push the packaging boxes to move in sequence along the direction of the guide plates to achieve packaging. During the operation of the workstation, when the material tray arrives at the station, a packaging box with open lid will be fed into the sealing equipment, and then a three-axis robot will pick up semi-finished products from the pallet and put them into the box, and the cylinder will push the packaging box to move along the direction of the guide plate. Under the guidance of the orientation of the guide plate, the box cover will tend to close, and a cylinder will push the box cover to close from top to bottom to form the final finished product. The final finished product is transported to the finished dock by the conveyor belt, and the AGV trolley is called to pick up the product and deliver it to the warehousing dock of the warehouse workstation.

3.6. Conveying Workstation. The conveying workstation is responsible for connecting the above workstations and carrying out smooth and accurate transmission of material pallets and finished products. The main equipment includes transmission line and AGV handling robot (AGV trolley). The transmission line drives the three-phase AC motor to drive the belt to run through the frequency converter, and the intercepting and jacking device is set at the assembly, marking, quality inspection and packaging workstation to block the pallet and lift it from the conveyor belt and position it to the processing position. AGV trolleys are programmable intelligent trolleys that are responsible for transporting finished products, defective products or empty pallets. The trolley adopts laser navigation and positioning

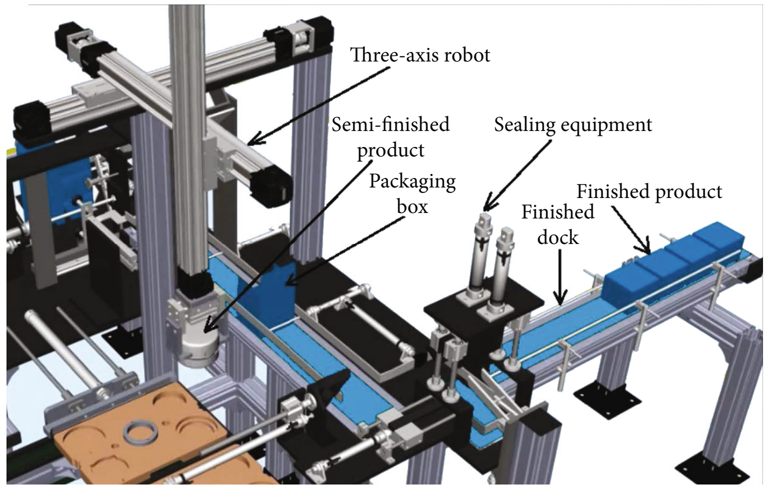

Figure 7: Packaging workstation.

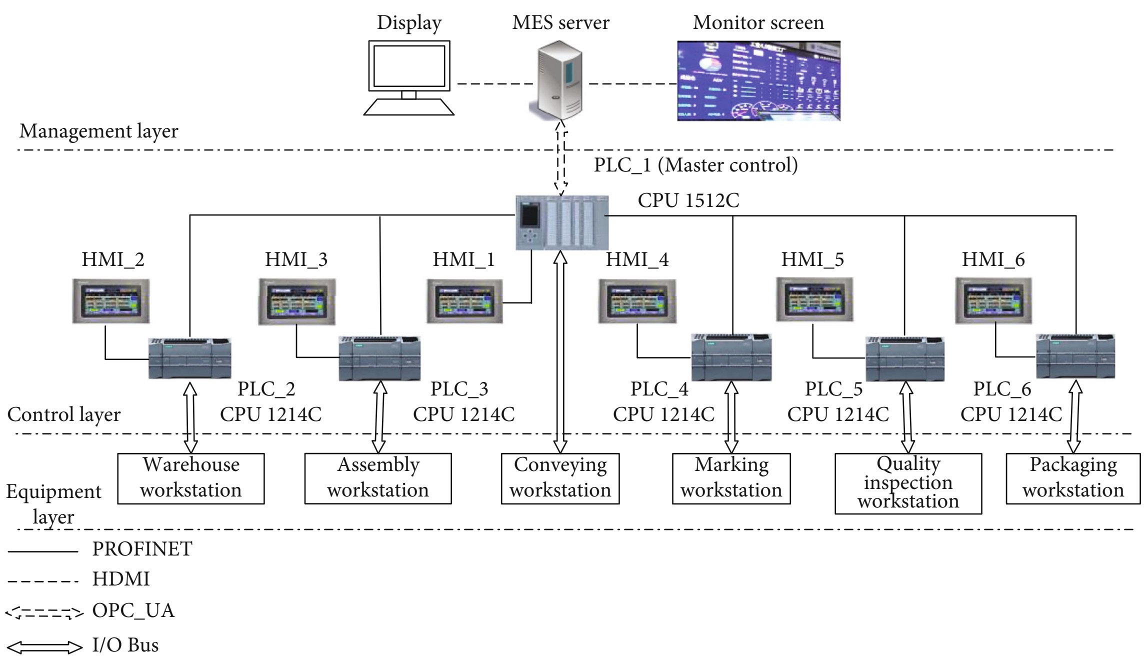

Figure 8: Production line architecture system.

and is equipped with ultrasonic sensors, which can realize trackless walking and automatic obstacle avoidance. The path planning file is imported into the system to control its driving route.

4. Production Line Architecture and Control System Design

4.1. Architecture System. The production line architecture system is designed with reference to the system level dimension of the intelligent manufacturing architecture. From bottom to top, it consists the equipment layer, the control layer and the management layer, as shown in Figure 8 [11]. The equipment layer is mainly the underlying hardware running in each workstation of the production line, including visual cameras, sensors, RFID and other sensing devices, as well as robots, laser marking machines, conveyor belts, cylinders and other execution equipment. The control layer is responsible for signal acquisition and controlling the operation of the underlying hardware, mainly includes PLC controllers and HMI touch screens at each site. The management layer is a set of production information management system (MES), including the server and monitoring screen, through the open OPC-UA protocol and the lower control PLC exchange data, to achieve online ordering, planning and scheduling, production scheduling, quality traceability, material inventory, data kanban and other management of the entire production line [12, 13].

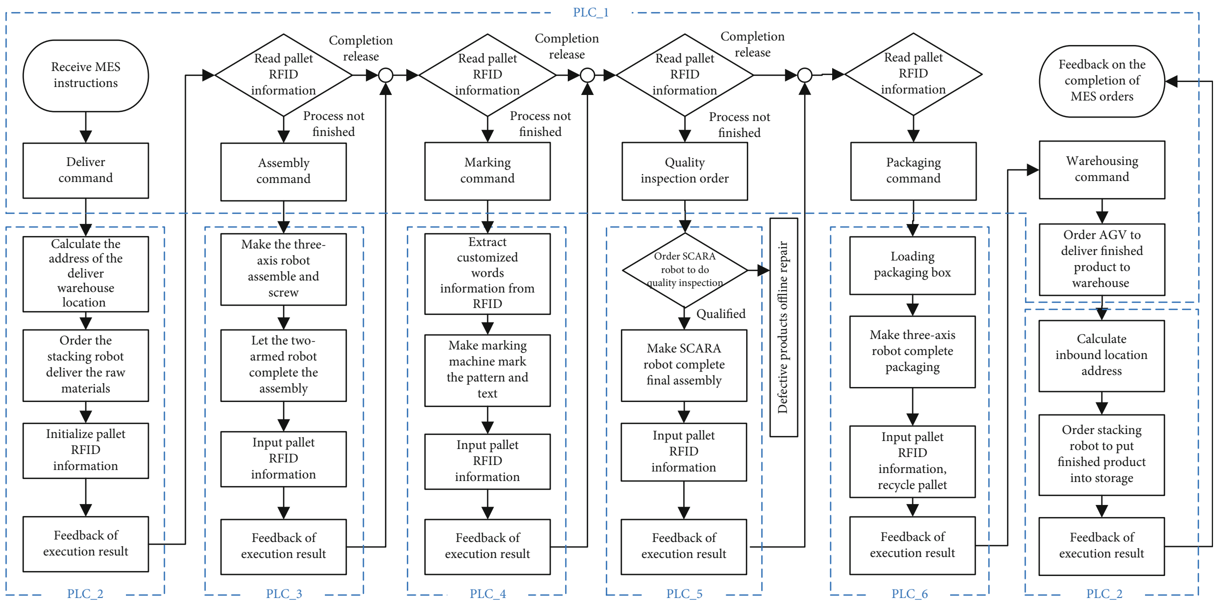

Figure 9: Control system program flow chart.

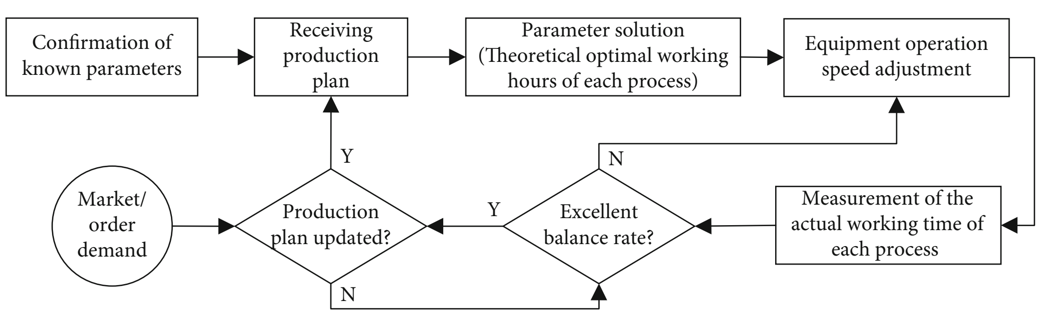

Figure 10: Realization of dynamic balance of production line.

4.2. Control System Design. The control layer in the architecture system is the bridge of communication between the upper and lower layers and the key to efficient operation of the entire production line. On the basis of this layer of hardware, a control system with PLC as the core is designed [14]. Each workstation is equipped with an independent PLC controller and HMI touch screen for real-time monitoring and control of field equipment. The PLCs are connected through switches, and the master-slave distributed structure is adopted as a whole. PLC of conveying workstation is used as the main control station, Siemens S7-1500 (CPU 1512C-1 PN) is selected, and OPC-UA Server is built in, which can exchange data with MES system through Client/Server communication. The rest of the workstation PLC is the slave station, Siemens S7-1200 (CPU 1214C DC/DC/DC). The hardware configuration of the control system, the design of human-machine interface and the programming of PLC control program are completed in TIA Portal V15, the Siemens integrated automation programming software. The communication between PLCs is realized by writing communication program and setting data exchange area [15]. The main control PLC is responsible for the overall linkage and coordination of the production line. It parses the task instructions issued by the MES, converts them into production orders, sends them to each slave station, and adjusts and controls the production process according to the feedback information from the slave stations. Each slave station PLC receives the command sent by the master station, controls the operation of the equipment in the station according to the specific technological process, and feeds back the execution result to the master station.

During the operation of the production line, the RFID electronic label flows with the material tray. The data in the label records the production information such as tray number, order ID, process, customization, quality and time in accordance with the agreed format, and the information is collected and updated at the RFID reader specially set up in each workstation. Using technical characteristics of RFID, like non-contact, fast identification, accurate and reliable, large capacity and repeatedly reading and writing can achieve production process control, progress tracking and benefit optimization [16]. The program flow of the whole production line is shown in Figure 9.

Table 1: Working hours of each process (unit: s).

Item	Process	Workstation	Adjustable range of working hours	Theoretical set value	Actual measured value
1	Raw material outbound	Warehouse workstation	$15 < t_1 < 35$	32.16	32.68
2	Component assembly	Assembly workstation	$30 < t_2 < 60$	32.33	32.55
3	Work-in-process marking	Marking workstation	$10 < t_3 < 20$	19.46	19.26
4	WIP quality inspection	Quality inspection workstation	$20 < t_4 < 50$	31.73	31.27
5	Semi-finished product packaging	Packaging workstation	$18 < t_5 < 40$	32.32	32.53
6	The finished warehousing	Warehouse workstation	$25 < t_6 < 65$	32.00	33.01

5. Dynamic Equilibrium Study

Production line balance is an important basis for manufacturing enterprises to achieve lean production. It is also an important embodiment of intelligent production line level [17]. All workstations of the production line in this paper belong to the type of controllable operation time. On this basis, a dynamic balance scheme of the production line is studied.

5.1. Establishment of Mathematical Model. The lean production method advocates zero inventory, emphasizing that companies should adjust their plans in a timely and swift manner following changes in market demand, and produce products in quantities that are "just right", excess products will cause greater losses [18]. An effective solution is to adjust the production speed in time according to the fluctuation of market demand and keep the production line in a better balance state. Specifically in this paper, the problem can be described as given the total production time of the "mini desktop vacuum cleaner", calculate the working time that should be allocated to each process to optimize the balance of the entire production line. The balance state of the production line is usually evaluated by the balance rate P. The larger the P value, the better the balance state, which should generally reach more than 85% [19]. This kind of problem belongs to the third type of production line balance problem (SLABP-III) [20], and the mathematical model can be established as follows:

Objective function:

$$\max (P) = \frac{\sum_{i=1}^{n} (t_i)}{n * \max (t_i)} * 100\% \quad (1)$$

Restrictions:

$$t_{sum} = \sum_{i=1}^{n} t_i \quad (2)$$

$$lb_i \le t_i \le ub_i \quad (i = 1, 2 \cdots, n) \quad (3)$$

In the formula, max (P) represents the maximum balance rate; t_i is the set value of the working hours of process i; n represents the number of processes; $\max(t_i)$ is the maximum working hours of all processes, that is, the working hours of the "bottleneck" process; t_{sum} is the total production time of the product; lb_i and ub_i represent the lower and upper limits of the working hours of process i, respectively. In the model, n, lb_i, and ub_i are all known parameters, t_{sum} is the value given by the user, and the parameter to be determined is t_i ($i = 1 \sim n$).

5.2. Model Parameter Solution Based on Genetic Algorithm. The mathematical model established in Equations (1)–(3) can be solved by intelligent optimization algorithms such as genetic algorithm, particle swarm optimization algorithm, and imperial competition algorithm. The genetic algorithm is used here, encode the parameters to be determined as chromosomes, and start from a set of randomly generated chromosome groups (ie. "populations"), simulating the "survival of the fittest" in the biological world. The evolution process of "survival of the individual", through several operations of selection, crossover and mutation of individuals in the group, identifies the optimal population to realize the parameter solution [21]. The process is mainly divided into the following steps [22]:

Step 1: Code the solution. Using floating-point encoding, each gene of chromosome T is represented by the decimal floating-point of parameter t_i ($i = 1 \sim n$) to be solved, that is, $T = \{t_1, t_2 \ldots, t_n\}$, gene values must meet the constraints of Equations (2) and (3).

Step 2: Initialize the population. M chromosomes are randomly generated as the initial solution.

Step 3: Fitness calculation. Taking formula (1) as the fitness function, the fitness value of each individual in the population is calculated. The larger the value is, the better the individual is.

Step 4: Competitive selection. Based on the fitness value of contemporary individuals, the roulette algorithm is used to select the better chromosomes as the new generation population.

Step 5: Crossover operation. A number of chromosomes are selected from the new generation population according to a given probability P_c, and a pair of random pairings are performed to generate new offspring, and the offspring chromosomes are used to replace the parent chromosomes.

Step 6: Mutation calculation. Select a number of chromosomes from the current population with a given probability P_m, and randomly select some components of the chromosome to perform mutation operations to change their gene values to obtain new individuals.

Step 7: Termination condition. If the population has met the preset evolution termination conditions, stop, and output the optimal individual in the current population as the optimal solution, otherwise go back to step 3.

5.3. Realization of Dynamic Balance. The basic principle of dynamic balance of production line is shown in Figure 10. It is realized by C# language programming in the Visual Studio development tool and integrated into MES system for production scheduling.

First, the known parameters of the model are determined according to the technological process and the hardware conditions of the production line. The number of processes in the "mini desktop vacuum cleaner" production line is $n = 6$. The adjustable range of workstations and working hours for each process is shown in the third and fourth columns of Table 1. Second, set the genetic algorithm parameters, population size $M = 100$, crossover probability $P_c = 0.4$, mutation probability $P_m = 0.1$ Then, the MES system receives the latest production plan, that is, the total production time of the product. Taking $t_{sum} = 180$ s as an example, after 51 iterations, the optimal individual {32.16, 32.33, 19.46, 31.73, 32.32, 32} is searched, and the theoretical optimal set value of the working hours of each process is obtained (see the fifth column of Table 1). Next, the MES sends the set value to the control layer, and the PLC is responsible for synchronously adjusting the running speed of the related equipment of the workstation (for example, the speed of the ABB robot can be adjusted by the SpeedRefresh command, and the speed of the conveyor belt can be adjusted by adjusting the frequency set value of the inverter and so on). Finally, the RFID tag on the material pallet is used to track the production process, and the actual working time of each process is recorded and fed back (see the sixth column of Table 1), and the balance rate of the production line is to be 91.5%, reaching an excellent level. The process is repeated until the production schedule is updated again to achieve dynamic balance of the production line.

6. Conclusion

The transformation and upgrading of the 3C industry to intelligent manufacturing is an inevitable trend to adapt to the development of the market. This article takes "mini desktop vacuum cleaner" as an example and refers to the concept of intelligent manufacturing and core technologies such as industrial robots, machine vision, RFID, PLC and MES to create a demonstration production line for 3C products and realize the intelligent production of this product. Aiming at the balance problem of the production line, a mathematical scheduling model is established, and genetic algorithm is used to solve the model parameters. Based on the above, the working speed of each underlying equipment is adjusted in real time to realize the dynamic balance of the entire production line. At present, the production line is running stably, and has reached the domestic advanced level as identified by the Guangdong Mechanical Engineering Society. It should be noted that the method of dynamic balance of production line in this paper is not only applicable to the manufacturing of products, but it can also be combined with the promotion and application of ERP system to procurement, sales, transportation and other links to achieve the balance of the whole production process for achieving a greater effect and for enterprises to lean production, which is the direction of further research in the future.

Data Availability

No data were used to support this study.

Conflicts of Interest

The author declares that they have no conflicts of interest.

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