Quality control in cyber-physical systems of smart electronics manufacturing

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Abstract. The creation of high-tech smart industries is observed in dynamically developing industries, which include the production of electronics and the automotive industry. The concept of “smart manufacturing” is closely related to the concept of cyber-physical systems, which integrates the main elements of digitalization and intellectualization. This concept provides for the continuous improvement of intellectual "cybernetic" resources for the effective management of the “physical” environment considered in this problem area. Improvement of technologies, ensuring high rates of reproducibility and suitability of equipment creates conditions for defect-free production. However, there remain the problems of recognizing patterns represented not by an obvious marriage, but by some not fully defined inconsistency on a set of requirements. The need to disclose uncertainties of this kind is typical for surface mounting technologies for printed circuit boards. The introduction of more and more advanced automatic optical inspections, containing the possibility of introducing intelligent (cybernetic) means, creates conditions for improving the quality of printed circuit boards as a “physical” environment. It is also important to minimize the "human factor", the presence of which is still used when making decisions on the results of control. In the article, ensuring the rhythm of digital production and increasing the reliability of control in quality management in smart high-tech industries using the example of electronics production.

1. Introduction
Smart production is presented as cyber-physical systems (CPS), where products are a physical subsystem, high technologies are a cybernetic subsystem. There are known methods of ensuring and assessing quality in the production of electronics and in high-tech industries, the transition to defect-free production is being carried out. The tasks of minimizing the human factor and introducing technological innovations to create digital intelligent industries are being solved. The main task is to minimize the human factor and introduce technological innovations. An urgent task is the creation of digital intellectual production facilities.

The line of automatic assembly under consideration in article includes a complex of modern automatic inspections at all stages of production (after a screen printer, after automatic installation of components and after a solder reflow oven). The control tools implemented in them (3D, RGB illumination, side cameras and online X-ray) form a large amount of control information, united in a common database for processing large amounts of data on the server.
Information processing ensures the introduction of intelligent technologies for making decisions about the quality of products, monitoring the fulfillment of the requirements of quality standards for each type of product.

An increase in the intellectual level of digital production technology will reduce the time spent by an employee of the Quality Control Department, to a value less than the cycle of production of products on an automated assembly line. In this technology, an employee of the Quality Control Department will accompany the optical inspection of products on the line, observing the rhythm of the automatic assembly of the conveyor. This will provide an increase in productivity and yield of suitable products, which is fundamentally unattainable by the old methods, and a decrease in the cost of production. The required efficiency is achieved by the correct choice of the existing technological equipment [1, 2]. The purpose of the article is to ensure the rhythm of digital production and increase the reliability of control in quality management in smart high-tech industries using the example of electronics production.

2. Materials and methods for the development of Industry 4.0 on the example of M2M interaction

Saki Self-Programming Software

The development of software (software) is becoming more and more relevant in the tasks of control of the production process in the automation of a technological line and the transition to a full 3D digital representation of the collected data. Sizes of products and components, time of operations, number of products in one batch.

Examples of modern standards and equipment are IPC-HERMES-9852 (The Hermes Standard for vendor independent machine-to-machine communication in SMT Assembly Version 1.1) [3] and Saki Self-Programming Software Accelerates 3D Inspection and M2M Communication [4].

The corresponding software ensures the functioning of the software-compatible equipment in the digital line. The more opportunities the software provides, the lower the costs incurred by the company in the production process. Saki Self-Programming Software is a seamless system that does not require the use of DFM. By simultaneously scanning different fields of view, the software captures the height and $XY$ data. At the same time, the software provides access to the library (database), which contains more than 300,000 components. Gerber and Centroid CAD data are required to program the unit.

Saki Self-Programming Software is working to improve the communication between installations as part of the development of the concept of Industry 4.0 and M2M interaction. This software provides machine calibration, diagnostics, maintenance, validation, data collection, and advanced reporting functions.

Electronics manufacturing technologies include different processes, however, the surface mounting of printed circuit boards (SMT) process is most dependent on the correct operation of the equipment, adherence to technological standards in accordance with GOST and adaptability to a quick changeover of software. In the most complete composition, the structure of SMT production (Saki America, Inc.) [5] is shown in figure 1.
These technological innovations and similar ones are designed to control the application of solder paste, and they also support feedback with a screen printer and a repair station. These installations are automated and, when defects appear, identified in the knowledge base, on the basis of which they work, they ensure their elimination. For example, if there is no solution in the knowledge base, then information on non-conformities is sent to a repair station, where further decisions are made by a specialist. The knowledge base is supplemented if necessary.

In this regard, an especially urgent task for modern production equipment is to prevent false failures at the end of the production process. The given error not only increases the delivery time of the finished product, but also leads to an increase in the labor intensity of manual control.

3. Simulation model of SMT production line assembly with RAM Commander

The production of electronics that meets the requirements of the standards is characterized by continuous quality control at every stage. Control of products in the production process is carried out by automatic optical inspection units (AOI). In the first two stages, optical inspection installations are built into the line in order to prevent the appearance of defects. At the last stage, the AOI in fact informs the operator about the defective product. Additional control of the installation in the form of a fluoroscopy unit is required to inspect the soldered joints of BGA components. For the maximum reduction of rejects, it is necessary to install the AOI system after each stage (figure 2), however, this requires a large investment.

![Figure 2. Arrangement of AOI installations in an automatic printed circuit assembly line.](image)

Optical control installations have been used for quite a long time to control production stages. However, until recently, only 2D inspection installations were used in factories, which do not allow control of a number of important parameters on which the quality of the batch produced directly depends (for example, for the stage of applying solder paste: volume, displacement, co-planarity, etc.) [6].

Quality $Q$ is defined as the degree of compliance with the requirements $R$, and each quality indicator $q_i$ corresponds to the requirement $r_i$. The degree of conformity is determined by quality control means and is numerically represented by the reliability of the control $R_e$.

$$Q = \{q_i\}$$

$$R = \{r_i\}$$

According [7] the probability of recognition of the object of control as satisfying the established requirements (suitable), provided that in reality it does not meet these requirements, i.e. represents defective product.

It should be noted that the probabilities of recognizing a suitable object as suitable, a defective object as defective, a suitable object as defective, and a defective object as suitable constitute a complete group of events [7], i.e.

$$P_{sg} + P_{sb} + P_{gb} + P_{gs} = 1$$  (2)
Modern automatic lines SMT are characterized by high reproducibility and suitability [8], therefore, the probability \( P_{gb} \) has rather low values and can be neglected. The reproducibility index \( C_p \) is guaranteed by the manufacturer, and the accuracy index \( P_p \) is ensured when the specified operating conditions are observed, therefore, the process of identifying suitable products as suitable and the opposite is not in doubt. Reducing the likelihood of \( P_{gb} \) is an urgent task.

The emergence of such a technological innovation as 3D inspection expands the ability of manufacturers to identify production defects at an early stage, as a result, to reduce the cost of repairing and disposing of defective products.

Technological innovations in the production of electronics include the emergence of machine-to-machine communication between units in the line.

For a detailed presentation of each stage of the production process and predicting the yield of suitable in the RAM Commander software package, 6 models were built (for each stage of the PP), simulating the procedure and demonstrating the current state of the SMT installation production line, as well as the results of the analysis of possible inconsistencies at each stage (figure 3).

Figure 3. Simulation of SMT production line assembly with RAM Commander software package.

The specifics of the manufacture of radio electronics are constantly increasing quality requirements. Debugging of production technology during the transition from a pilot sample and an initial batch to serial production leads to a decrease in the number of defective products to indicators standardized in units of \( P_{pm} \), that is, to a transition to defect-free production. However, this should take into account the technical characteristics of controls, the use of which is characterized by a significant \( P_{gb} \) value, when a suitable product is classified as “nonconforming product”, and the intervention of a human operator is required to make a final decision. This not only creates risks associated with the ”human factor”, but also disrupts the rhythm of the automatic conveyor for recognizing the emerging uncertainties.

This implies the need to solve two problems:

1) minimization of the ”human factor”, at least to ensure the rhythm of the conveyor.

\[
M = \frac{T_v}{P},
\]

where \( M \) (measure) is the cycle of the production line, \( T_v \) is the valid actual operating time of the SMT line in a specific time period (min., sec.), \( P \) is a given production program in accordance with the technological capabilities of a specific production equipment.

\[
K_r = M \cdot n_p,
\]

where \( K_r \) is the rhythm factor of the production line, \( M \) (measure) is the cycle of the production line, \( n_p \) is the number of products.
2) ensuring the reliability of the control system, provided that its performance is sufficient in terms of the performance of the entire automatic line. From (2) it follows that the actual is the probability of attributing a really suitable object to defective \( P_{gb} \), which is given by the expression [7].

\[
P_{gb} = \int_{-\infty}^{C} f(x) \int_{C-x}^{\infty} \phi(\xi)d\xi dx,
\]

where \( f(x) \) is the probability density of the distribution of the controlled quantity; \( \phi(\xi) \) is the probability density of the error in estimating the value of the controlled quantity \( x \).

One of the key features of using the RAM Commander software package when modeling an SMT line was the ability to import data and embed existing program code containing expert systems in organizing production processes, methods and tools for monitoring production and related processes. Determination of the numerical values of quality indicators was carried out by calculation-experimental method. An example of detecting false failures and the procedure for the results of analyzing possible malfunctions at the stage of loading printed circuit boards are shown in figure 4.

![Figure 4](image)

**Figure 4.** The procedure and results of the analysis of possible malfunctions at the stage of screen printing.

Red color in the figure marks the name and number of inconsistencies of regulatory documents identified using the model and fuzzy regulator.

4. Development of a model of an intelligent control system for organizing the process of automatic installation of radio electronics products

The control of the production process can be replaced by an intelligent control system, which is a fuzzy regulator with the possibility of introducing or excluding the necessary conditions for the functioning of the technological process with subsequent self-learning.

The main elements of the control system: \( e \) - entrance, \( o \) - output, \( S_1, S_2, S_3 \) and \( S_4 \) - control units and intelligent integrators of SPI and AOI inspections (figure 5).
The stability of the automatic control system is ensured by maintaining the structure at small and tending to 0 values of the error. If this condition is met, the transient process decays over time, and the system goes into a stable position.

In this case, the transient process is equal to (6):

$$a_0 e^{(n)}(t) + a_{n-1} e^{(n-1)}(t) + \ldots + a_1 e'(t) + a_0 e(t) =$$

$$= b_m e^{(m)}(t) + b_{m-1} e^{(m-1)}(t) + \ldots + b_1 e'(t) + b_0 e(t)$$

(6)

Thus, after the end of the transient process, the stability value is determined at the output. In a stable position, all derivatives are equal to 0, and the equation of the transient process has the form (7):

$$a_0 y = b_0 e_0$$

(7)

where (7):

$$y = \frac{b_0 e_0}{a_0}$$

(8)

The necessary improvement in the quality indicators of electronic products is associated with the operation of manufactured products under conditions of external influencing factors, primarily mechanical and climatic. The high level of quality of installation of products is ensured by the implementation of an increasing number of stages of the digital life cycle and the introduction of technological innovations into the production process. The defining functions are implemented in the form of electronic programmable means and intelligent control systems.

The simulation made it possible to identify possible types and consequences of failures, to determine the influence of various events on the criticality of failures, to rank the priority numbers of risk and criticality of failure, and also to significantly supplement the developed integrated database of production processes.

5. Results

The specifics of the manufacture of radio electronics are constantly increasing quality requirements. The necessary improvement in the quality indicators of electronic products is associated with the operation of the manufactured products in conditions of external influencing factors, primarily mechanical and climatic. A high level of quality in the installation of products is ensured by the implementation of an increasing number of stages of the digital life cycle and the introduction of technological innovations in the software. The results presented allowed us to correctly organize the rhythmic work of the PP and minimize the “human factor”. The use of the RAM Commander software package made it possible to build 6 models (for each stage of the PP), simulating the procedure for carrying out and demonstrating...
the current state of the SMT assembly production line. It is shown that the control of the production process can be replaced by an intelligent control system, which is a fuzzy regulator with the possibility of introducing or excluding the necessary conditions for the functioning of the technological process with subsequent self-learning. The considered tasks of introducing digitalization components are characteristic of cyber-physical systems that determine the vector of development of smart industries. The necessary attention is paid to the tasks of ensuring the reproducibility, suitability and stability of the PCB production line for SMT assembly.

6. Discussion
Further improvement of the software is determined by the intellectualization of the applied inspections. Advances in cybernetics related to pattern recognition, represented by images or a set of parameters, create conditions for minimizing the probability of false refusals. Such approaches can be implemented using fuzzy logics and neural networks, databases, knowledge bases to disclose uncertainties and achieve defect-freeness.

An important role is also played by the correct assessment of the quality indicators of both products and the inspections themselves. Metrological support of known inspections is based on the use of statistical methods (8) and the achievement of the specified values of reproducibility and suitability of processes. At the same time, the tasks of attestation of control samples are solved only at the level of manufacturing firms of inspections and are subject to conformity confirmation procedures. Potential inconsistencies can also create uncertainty.

7. Conclusion
The intensive development of electronics production causes the need for continuous improvement of production processes. The article set a pragmatic goal - to ensure the rhythm of digital production and increase the reliability of control. However, achieving this goal is associated with quality management in smart high-tech industries. The results presented briefly characterize the direction of the authors’ work. Further re-search is related to the methods of intellectualization of inspections and the implementation of machine-to-machine communication. The authors consider the improvement of the metrological support of electronics production to be another important direction.

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