Control model of technological operations of mounting automatic printed circuit boards based on a multiparameter fuzzy classifier

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Abstract. In the context of creating digital production, ensuring the concept of continuous support for the product life cycle and the use of big data management systems contributes to the creation of a permanent relationship between all computer-aided design systems implemented at the enterprise. The purpose of the article is to develop a procedure for ensuring the quality of electronic products based on the introduction of intelligent equipment for automatic installation of printed circuit boards based on a multiparameter self-learning fuzzy classifier. To solve the problems of interfacing big data management systems and modern computer-aided design systems, it is proposed to apply the methods of discrete linear or mixed integer programming. Application of logical operations will allow one to simulate the production process in more detail and predict possible disturbances with maximum accuracy.

1. Introduction

The introduction of elements of the digital production concept is especially important at enterprises manufacturing electronic products that are in demand in all spheres of human activity. To create new objects that implement the concept of digital production, it is necessary to introduce technological innovations in the electronics production, which requires an analysis of the system properties of the production means and quality assurance. The aim of the article is to develop a model for managing technological operations for automatic assembly of printed circuit boards based on a multiparameter self-learning fuzzy classifier.

The controlled manufacturing process of manufacturing electronics in a structural mathematical modeling package consists of seven elements of the manufacturing process (Figure 1), namely:
1. loading operation of circuit boards and components;
2. solder printing operation;
3. Solder Paste Inspection;
4. operation of component placement;
5. oven operation;
6. operation of laser marking;
7. operation of automatic optical inspection.
Technologies for automatic installation of printed circuit boards are constantly evolving, but the composition of the equipment remains consistent with the basic structure. The improvement and miniaturization of the electronic component base places new demands on the hardware, as well as on the software package. The electronics manufacturing process consists of seven stages, presented in Figure 1. The highest risk of defect occurrence is caused by operations performed by a human, represented as control action (CA) [1].

Intellectual solutions in the field of machine-to-machine interaction (M2M) play a special role in the development of the Internet of things (IoT). New opportunities for ensuring the quality of electronic products are opening up both on the basis of the increasingly complete “digitalization” of production, and on the transition to a full digital product life cycle.

The introduction of technological innovations implies the use of new functional and information equipment, envisaged by the concept of digital production through the use elements of the M2M concept, DFM (design for manufacturing - design with technological requirements), ID-identifiers. Technical re-equipment is aimed at improving the consumer properties of the products produced, which together determine its quality, as well as at increasing the technological flexibility of the production process (PP). For this purpose, it is necessary to build in the production process logical or fuzzy operations performed by production equipment on the basis of pre-defined knowledge bases and rules.

The end-to-end digital design of the PP is the transfer of the simulation results from one stage to the next in a single design environment. At the same time, changes made at any stage should be displayed in all parts of the project.

The design process of electronics consists of three main stages:
1. system engineering (external and structural design);
2. circuit design (development and analysis of designed circuits and selection of diagnostic (test) tests);
3. technical.

2. Mathematical model of the technological line structure of automatic installation printed circuit boards

The functional complexity of the end-to-end digital design of the technological process is explained by the multiple modeling of the production stages. The complexity of the end-to-end simulation is to attract a large number of participants with a high level of detail and use of the most complex information technologies (computer-aided design systems and data management systems).

In the context of creating digital production, ensuring the concept of continuous support for the product life cycle and the use of big data management systems contributes to the creation of a permanent relationship between all computer-aided design systems implemented in the enterprise. One of the connecting tasks of creating continuous production is its flexibility, consistency of the systems used and the integrity of the use of information systems in production. Thus, the problem of the end-to-end digital design process of electronics and the development of software pairing methods for big data management systems and modern computer aided design systems has a high level of relevance and practical significance.

The introduction of technological innovations in the enterprise in the form of computer-aided design and the management of large amounts of data is carried out by replacing successive interoperational links at the stages: testing solder paste and automatic optical inspection - with enlarged operators of
steps 3 and 7. Replaced operators is a solution to a mixed optimization problem with linearity and production model nonlinearity with training at stages 3 and 7 (Fig. 2).

Figure 2. Stages of the production process, using an intelligent self-learning system of machine-to-machine interaction, built on the basis of the apparatus of fuzzy logic

In production process control tasks during process line automation, some variables can take several discrete values. This is due to large amounts of data for selecting suitable variables for the organization of production, such as: dimensions of products, production time, number of products in one batch. To solve the problems of interfacing big data management systems and modern computer-aided design systems, it is proposed to apply the methods of discrete linear or mixed integer programming. Application of logical operations will allow one to simulate the production process in more detail and predict possible disturbances with maximum accuracy.

3. The method of software interface of big data control systems in the organization of electronics production using discrete linear and mixed integer programming

One of the prerequisites for the use of this method is the simultaneous recording and tracking of discrete and continuous parts. A mixed optimization problem with a nonlinearity of the system will look like (1):

$$
\begin{align*}
Q(x, y) &= \min \\
J(x, y) &\leq 0 \\
x &\in X \\
y &\in Y, y \subseteq \mathcal{Z}
\end{align*}
$$

where $Q(x, y)$ – the convex function of the maximum allowable resources $y$ for the production of products $x$,

$J(x, y)$ – a convex function of resource consumption $y$ for producing $x$,

$X$ – multiple resource values,

$Y$ – plural values of products.

A mixed optimization problem with a linear system will look like:
\begin{equation}
Q(x, y) = \Rightarrow \min
\begin{cases}
  f(x) = 0; \ i = 1, ..., 1 \\
  Y_i(x) \leq 0; \ i = n + 1, ..., p \\
  x \in \mathcal{C}_i \mathcal{C}_i(c_{i1}, ..., c_{ig1}) \\
  x_{ig} \leq x_i \leq x_{if}; \ i = 1, m_c + 1, ..., m
\end{cases}
\end{equation}

In order to simplify the system, additional restrictions were introduced (3):
\begin{equation}
\begin{cases}
  x_i = R_{i1} C_{i1} + \cdots + R_{ig1} C_{ig1} \\
  R_{ij} \in \{0; 1\}, j = 1, ..., q_i \\
  R_{i1} + \cdots + R_{ig1} = 1
\end{cases}
\end{equation}

where $C_i$ – multiple values of demand for item $i$ by request of a $c_{ig}$ in the amount of $g$.

Planning of the production process is performed using a mixed linear task, determined by the objective function:
\[
\min \sum_{i \in M} \sum_{k \in K} l_{ik} x_{ik} \leq y_{ik}.
\]

For the correct use of the function, the following additional conditions are introduced:
\begin{equation}
\begin{cases}
  l_{ik} = l_{ik-1} + x_{ik} \sum_{j \in L} l_{ij} x_{ik} - c_{ik} \\
  \sum_{j \in L} z_{ai} x_{ik} \leq U_{ai} \\
  x_{ik} \leq S H_{ik} \\
  l_{ik-1} \geq 0 \\
  x_{ik} \geq 0 \\
  y_{ik} \in \{0; 1\}
\end{cases}
\end{equation}

To ensure system stability, a mixed linear problem using the integer linear programming method is defined by the function:
\[
R = \sum_{i = 0}^{M} (\sum_{k = 1}^{K} D_i y_{ik} + P_i l_{ik} + V_{ik} x_{ik}) .
\]

For the correct use of the function, the following additional conditions are introduced:
\begin{equation}
\begin{cases}
  l_{ik-1} + x_{ik} - E_i - c_{ik} - \sum_{j < i} l_{ij} x_{ik} = l_{ik} \\
  \sum_{z_{wk}} (G_{ik} y_{ik} + z_{lw} x_{ik}) \leq C_{wk} \\
  x_{ik} \leq H y_{ik}; i = 1, ..., M; k = 1, ..., K \\
  x_{ik} l_{ik} \geq 0; i = 1, ..., M; k = 1, ..., K \\
  x_{ik} \{0; 1\}; i = 1, ..., M; k = 1, ..., K
\end{cases}
\end{equation}

where $M$ – number of products, $T$ – time intervals, $W$ – volume of production resources, $G_{iw}$ – the set time for product $i$, $Z_{iw}$ – production rate of the product, $U_{iw}$ – power production resources (the volume of the productive base of the enterprise), $c_{iw}$ – product demand (demand), $J_{ik}$ – the number of units of products $i$ required in the production of units of $j$, $E_i$ – time intervals in the manufacture of products $i$ (idle), $V_{iw}$ – variable technological innovations introduced into production processes.

For the phased introduction of digital technology in the production of electronics, a database for quality control systems Solder Paste Inspection (SPI), Automated Optical Inspection (AOI) and an integrated database of the entire production process are created. Creating an intelligent software system requires computer programs built on the basis of fuzzy logic and allowing the machine to make its own decisions, which improves the efficiency of the PP of manufacturing electronics products. When
developing a model of the production process, it is required to make operational details of the technological process.

Stabilization of the output signal of large data management systems and computer-aided design of machine-to-machine interaction at the SPI and SPI-AOI stages is provided by two input variables in the normalization block, namely: error and error rate (Fig. 3):

\[
\frac{df(n)}{dt} = q - g
\]

\[
(n) = (n) - (n-1).
\]

**Figure 3.** Model of fuzzy control of the manufacturing process of manufacturing electronics

The dynamics of quality assurance due to the phased use of the technological operations control model of automatic mounting of printed circuit boards based on a multiparameter fuzzy classifier with training is presented in figure 4.

**Figure 4.** Dynamics of quality assurance using a fuzzy regulator: (a) - reduction in defect rates to 92.1%; (b) - reduction in defect rates to 95.8%; (c) - reduction in defect rates to 96.1%; (d) - reduction in defect rates to 99.3%.

The analysis of the presented graphs confirms a steady increase in the level of reliability and sustainability of the PP. The developed model makes it possible to unify and typify the production process and their elements at various enterprises of the electronic industry using the PP sequence model, which ensures the gradual replacement of the human factor by technological innovations.
To implement the model, a database and a computer program for controlling the process of automatic electronics installation using a multi-parameter fuzzy controller has been developed. The database is designed to manage the process of automatic installation of electronics, namely, accounting, systematization and analysis of the consequences of possible types of inconsistencies. Process control is made on the basis of decision making on the amount of deviation. The specified parameters in the database are interpreted as: H-low, Y-moderate, B-high quality products. The database records defect for each batch, tracks and clustering by defect type at the stages of soldering paste testing (SPI) and automatic optical inspection (AOI), and simplifies the search and selection of defect elimination based on the multiparameter fuzzy controller entered into the database.

4 Conclusion
Using the principles of automated control systems and digital design throughout the production cycle will reduce the temporal characteristics of the PP, and therefore the operating costs of jobs.

The developed models make it possible to assess the proportion of non-conforming products and the final defect and ensure high quality indicators when introducing technological innovations. Integration of information obtained from the elements of digital production and operational knowledge in the knowledge base will improve the quality of electronic products and minimize the human factor.

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