MINISTRY OF EDUCATION AND SCIENCE OF UKRAINE
NATIONAL AVIATION UNIVERSITY
Faculty of Aeronavigation, Electronics and Telecommunications
Department of computer integrated complexes

ADMIT TO DEFENSE
Head of the graduating department
__________ Sineglazov V.M.
“_____”_________________2024.

QUALIFICATION WORK
(EXPLANATORY NOTE)

OF THE GRADUATE OF THE EDUCATIONAL DEGREE
“BACHELOR”

Specialty 151 "Automation and computer-integrated technologies"
Educational and professional program "Computer-integrated technological processes and production"

Theme: Automated system for preparing printed circuit boards based on a laser engraver

Performer: student of IK-421 Ba group Salmi Mykola Olehovych
Supervisor: Professor Sineglazov Victor Myhailovych

Norm controller: ___________ Filyashkin M.K.
(sign)

Kyiv – 2024

МІНІСТЕРСТВО ОСВІТИ І НАУКИ УКРАЇНИ

НАЦІОНАЛЬНИЙ АВІАЦІЙНИЙ УНІВЕРСИТЕТ

Факультет аеронавігації, електроніки та телекомунікацій

Кафедра авіаційних комп'ютерно-інтегрованих систем

ДОПУСТИТИ ДО ЗАХИСТУ

Завідувач випускової кафедри

______ Віктор СИНЄГЛАЗОВ

“____” ______________2024 р.

КВАЛІФІКАЦІЙНА РОБОТА

(ПОЯСНЮВАЛЬНА ЗАПИСКА)

ВИПУСКНИКА ОСВІТНЬОГО СТУПЕНЯ

“БАКАЛАВР”

Спеціалність 151 "Автоматизація, та комп’ютерно-інтегровані технології"

Освітньо-професійна програма "Комп’ютерно-інтегровані технологічні процеси і виробництва"

Тема: Автоматизованан система підготовки друкуваних плат на базі лазерного гравера

Виконавець: студент групи ІК-421 Ба Сальмі Микола Олегович

Керівник: професор Синєглазов Віктор Михайлович

Нормоконтроллер: ___________ Філяшкін М.К.

(підпис)

Київ – 2024

NATIONAL AVIATION UNIVERSITY
Faculty of Aeronautics, Electronics and Telecommunications
Department of aviation computer-integrated systems

Educational degree: Bachelor
Specialty 151 "Automation and computer-integrated technologies"
Educational and professional program "Computer-integrated technological processes and production"

APPROVED
Head of department
__________ Sineglazov V.M.
“____” ____________2024.

TASK
For the student’s thesis
by: Salmi Mykola Olehovych

1. **Thesis topic** (project topic) “Automated system for preparing printed circuit boards based on a laser engraver”
2. **Deadline for an execution of a project**: from May 10 of 2024 to June 3 of 2024
3. **Initial data for the project**: To study and review the process of designing an automated system for the preparation of printed circuit boards based on a laser engraver.
4. **Contents for explanatory note:**

1. Overview of printed circuit board manufacturing methods. 2. Analysis of existing systems. 3. Identification of advantages and disadvantages of existing

solutions. 4. Definition of the main functions of the automated system. 5. Development of software for controlling a laser engraver.

5. List of required graphic material: tables.

6. Calendar schedule-plan:

№	Task	Execution term	Execution mark
1.	Getting the task	01.04.2024 – 02.04.2024	Done
2.	Formation of the purpose and main objectives of the study	02.04.2024 – 14.04.2024	Done
3.	Analysis of existing methods	15.04.2024 – 30.04.2024	Done
4.	Theoretical consideration of problem solving	01.05.2024 – 05.05.2024	Done
5.	Analysis of algorithm for designing an industrial automation system using CAD software	06.05.2024 – 25.05.2024	Done
6.	Preparation of an explanatory note	26.05.2024 – 29.05.2024	Done
7.	Preparation of presentation and handouts	01.06.2024 – 03.06.2024	Done

7. Task issue date: 01 “April” 2024.

Supervisor: __________________________ Sineglazov V.M.

(sign)

Task is taken for completion by: ________________ Salmi M.O.

(sign)

НАЦІОНАЛЬНИЙ АВІАЦІЙНИЙ УНІВЕРСИТЕТ

Факультет аеронавігації, електроніки та телекомунікацій

Кафедра авіаційних комп’ютерно-інтегрованих комплексів

Освітній ступінь: Бакалавр

Спеціальність 151 "Автоматизація та комп’ютерно-інтегровані технології"

Освітньо-професійна програма "Комп’ютерно-інтегровані технологічні процеси і виробництва"

ЗАТВЕРДЖУЮ

Завідувач кафедри

_____ Віктор СИНЄГЛАЗОВ

“____” __________2024 р.

ЗАВДАННЯ

на виконання кваліфікаційної роботи студента

Сальмі Микола Олегович

1. Тема роботи “Автоматизована система підготовки друкованих плат на базі лазерного гравера”

2. Термін виконання роботи: з 10.03.2024 по 03.06.2024

3. Вихідні дані до роботи: Вивчити та переглянути процес проектування автоматизованої системи підготовки друкованих плат на базі лазерного гравера.

4. Зміст пояснювальної записки (перелік питань, що підлягають розробці):

1. Огляд способів виготовлення друкованих плат. 2. Аналіз існуючих систем. 3. Визначення переваг і недоліків існуючих рішень. 4. Визначення основних

функцій автоматизованої системи. 5. Розробка програмного забезпечення для керування лазерним гравером.

4 **Перелік обов’язкового графічного матеріалу**: таблиці.

5 **Календарний план-графік:**

№	Завдання	Термін виконання	Відмітка про виконання
1.	Отримання завдання	01.04.2024 -02.04.2024	Виконано
2.	Формування мети та основних завдань дослідження	02.04.2024 – 14.04.2024	Виконано
3.	Аналіз існуючих методів	15.04.2024 – 30.04.2024	Виконано
4.	Теоретичний розгляд вирішення поставлених завдань	01.05.2024 – 05.05.2024	Виконано
5.	Аналіз алгоритму проектування систем промислової автоматизації з використанням необхідного програмного забезпечення	06.05.2024 – 25.05.2024	Виконано
6.	Оформлення пояснювальної записки	26.05.2024 – 29.05. 2024	Виконано
7.	Підготовка презентації та роздаткового матеріалу	01.06.2024 – 03.06.2024	Виконано

6 Дата видачі завдання ___ «01» березня 2024р.

Керівник: ______________________ Синєглазов В.М.

(підпис)

Завдання прийняв до виконання: ______________ Сальмі М.О.

(підпис)

ABSTRACT

Explanatory note of qualification work “Automated system for preparing printed circuit boards based on a laser engraver”

The object of research is the process of preparing printed circuit boards

The subject of research is the methods and means of automating the process of preparing printed circuit boards based on a laser engraver

Purpose of qualification paper is the research and development of an automated system for preparing printed circuit boards based on a laser engraver

Research method is the analysis of existing systems, processing of literary sources

The set tasks were successfully solved and the goal of the research was achieved. The developed automated system for the preparation of printed circuit boards based on a laser engraver allows to increase the efficiency, accuracy and environmental friendliness of the production of printed circuit boards, and also provides the possibility of rapid reconfiguration for the production of new types of boards and adaptation to changes in production needs.

The results of the work are of practical importance for enterprises of the electronic industry and can be implemented in production to increase competitiveness and reduce the cost of production.

РЕФЕРАТ

Пояснювальна записка до кваліфікаційної роботи "Автоматизована система підготовки друкованих плат на базі лазерного гравера"

Об'єктом дослідження є процес виготовлення друкованих плат

Предметом дослідження є методи та засоби автоматизації процесу виготовлення друкованих плат на базі лазерного гравера.

Метою кваліфікаційної роботи є дослідження та розробка автоматизованої системи підготовки друкованих плат на базі лазерного гравера.

Методом дослідження є аналіз існуючих систем, опрацювання літературних джерел

Поставлені завдання успішно вирішено і мета дослідження досягнута. Розроблена автоматизована система підготовки друкованих плат на базі лазерного гравера дозволяє підвищити ефективність, точність і екологічність виробництва друкованих плат, а також забезпечує можливість швидкої переналаштування для виробництва нових типів плат. та адаптація до змін виробничих потреб.

Результати роботи мають практичне значення для підприємств електронної промисловості та можуть бути впроваджені у виробництво для підвищення конкурентоспроможності та зниження собівартості продукції.

CONTENT

1. INTRODUCTION
1.1 Determination of topic relevance.

In today's world of electronics and technology, printed circuit boards play a key role in the functioning of various devices. From simple household appliances to complex industrial systems - printed circuit boards are the basis for placing and connecting electronic components [1, p. 5]. With the growing demand for electronic devices and increasing their functionality, there is a need for fast and efficient production of printed circuit boards.

Traditional PCB manufacturing methods, such as chemical etching and mechanical milling, have certain drawbacks. Chemical etching requires the use of hazardous substances, which can have a negative impact on the environment and human health. Mechanical milling, in turn, has limitations regarding the complexity and accuracy of printed circuit boards. Therefore, it is urgent to search for alternative methods of manufacturing printed circuit boards that would ensure high accuracy, speed and environmental friendliness of the process.

One of the promising directions in the production of printed circuit boards is the use of laser technologies. Laser engraving allows you to achieve high accuracy and speed of manufacturing printed circuit boards, while reducing the impact on the environment [4, p. 45]. Automation of the process of preparing printed circuit boards on the basis of a laser engraver allows to significantly increase the efficiency and productivity of production.

The relevance of the topic "Automated system for preparing printed circuit boards based on a laser engraver" lies in the need to develop and implement modern methods of manufacturing printed circuit boards that would ensure high accuracy, speed and environmental friendliness of the process [5, p. 8]. Automation of the process of preparing printed circuit boards allows to reduce the influence of the human factor, increase the stability and repeatability of results, and also reduce the time of the production cycle.

Research and development of an automated system for the preparation of printed circuit boards based on a laser engraver is of great importance for the development of the electronic industry. Such a system will allow to optimize the process of manufacturing printed circuit boards, reduce production costs and improve the quality of the final product. In addition, automation of the process of preparing printed circuit boards will contribute to reducing the impact on the environment, since laser engraving does not require the use of chemicals.

The topicality of the topic is also due to the growing need for rapid prototyping and small-scale production of printed circuit boards. An automated system for preparing printed circuit boards based on a laser engraver will significantly reduce the time for development and production of prototypes, which is especially important for innovative projects and startups.

Research and development of an automated system for preparing printed circuit boards based on a laser engraver are of practical importance for various industries where electronic devices are used [8, p. 67]. Such a system can find application in the production of medical equipment, automotive electronics, household appliances, automation systems and control of technological processes.

In addition to industrial application, the automated system for preparing printed circuit boards based on a laser engraver can be used in educational institutions and research laboratories [9, p. 89]. Students and researchers will have the opportunity to quickly and efficiently produce printed circuit board prototypes for their projects, which will contribute to the development of innovative ideas and increase the quality of education.

The topicality of the topic is also related to the need to optimize production processes and reduce production costs. An automated system for the preparation of printed circuit boards based on a laser engraver will reduce the time for the production of printed circuit boards, reduce the number of defects and increase the efficiency of the use of materials. This, in turn, will lead to a decrease in the cost of production and an increase in the competitiveness of enterprises.

Thus, the relevance of the topic "Automated system for preparing printed circuit boards based on a laser engraver" is due to the need to develop modern methods of manufacturing printed circuit boards that ensure high accuracy, speed and environmental friendliness of the process. Research and development of such a system is of practical importance for various industries, educational institutions and research laboratories. Automation of the process of preparation of printed circuit boards will allow to optimize production processes, reduce production costs and improve the quality of the final product.

1.2 Formulation of the goal and objectives of the research.

The relevance of the topic "Automated system for preparing printed circuit boards based on a laser engraver" lies in the need to improve the process of manufacturing printed circuit boards in order to increase the efficiency, accuracy and environmental friendliness of production [11, p. 23]. In the conditions of the rapid development of the electronic industry and the growing demand for electronic devices, traditional methods of manufacturing printed circuit boards are becoming insufficiently efficient and do not meet modern requirements.

Laser engraving, as one of the promising methods of manufacturing printed circuit boards, has a number of advantages compared to traditional methods. It allows you to achieve high precision and clarity of printed circuit board elements, rapid prototyping and small series production, and also reduces the impact on the environment due to the absence of the use of chemicals.

However, the process of preparing printed circuit boards using a laser engraver requires automation to ensure stability and repeatability of results [13, p. 78]. An automated system for preparing printed circuit boards allows you to minimize the impact of the human factor, reduce the time for setting up and maintaining equipment, and also increase production productivity.

The topicality of the topic is also due to the need to reduce costs for the production of printed circuit boards [14, p. 91]. Automation of the process of preparing printed circuit boards based on a laser engraver allows you to optimize the use of materials, reduce the amount of waste and defects, as well as reduce energy consumption. This, in turn, leads to a decrease in the cost of production and an increase in the competitiveness of enterprises.

In addition to economic advantages, the automated system for preparing printed circuit boards based on a laser engraver has environmental advantages [15, p. 56]. Laser engraving does not require the use of chemicals such as acids and alkalis used in chemical etching. This allows you to avoid the generation of hazardous waste and reduce the negative impact on the environment.

The topicality of the topic is also related to the possibility of rapid prototyping and small-scale production of printed circuit boards. An automated system for preparing printed circuit boards based on a laser engraver allows you to significantly reduce the time for development and production of prototypes, which is especially important for innovative projects and startups. Rapid prototyping allows you to quickly check and improve the design of printed circuit boards before starting serial production.

Research and development of an automated system for preparing printed circuit boards based on a laser engraver are of practical importance for various industries [17, p. 67]. Such a system can find application in the production of medical equipment, automotive electronics, household appliances, automation systems and control of technological processes. This will improve the quality and reliability of electronic devices, as well as reduce the time for their development and production.

The topicality of the topic is also due to the need to improve the qualifications of specialists in the field of electronics [18, p. 89]. An automated system for preparing printed circuit boards based on a laser engraver requires special knowledge and skills for effective use. Research and development of such a system will contribute to the training of highly qualified specialists capable of working with modern equipment and technologies.

In addition to industrial application, the automated system for preparing printed circuit boards based on a laser engraver can be used in educational institutions and research laboratories [19, p. 102]. Students and researchers will have the opportunity to acquire practical skills in the design and manufacture of printed circuit boards, which is essential for their professional development.

The topicality of the topic is also related to the possibility of integrating the automated system for preparing printed circuit boards with other production automation systems [20, p. 45]. This will make it possible to create complex solutions for the management of production processes, increase the efficiency and flexibility of production, as well as provide the possibility of remote control and monitoring.

Research and development of an automated system for preparing printed circuit boards based on a laser engraver will contribute to the development of the domestic electronics industry [21, p. 78]. The implementation of such a system will increase the competitiveness of Ukrainian enterprises on the world market, increase the volume of production and export of electronic devices, as well as create new jobs for highly qualified specialists.

The relevance of the topic is also due to the need to reduce dependence on imported components and equipment [22, p. 91]. The development and implementation of domestic automated systems for the preparation of printed circuit boards will reduce dependence on foreign suppliers, reduce costs for the purchase of equipment and components, and also ensure the technological independence of the country.

Research and development of an automated system for preparing printed circuit boards based on a laser engraver is important for the development of science and innovation in Ukraine. Such research contributes to the development of fundamental and applied sciences, stimulates innovative activity and increases the scientific and technical potential of the country.

The topicality of the topic is also related to the possibility of commercialization of research results [24, p. 34]. The development and implementation of an automated system for the preparation of printed circuit boards based on a laser engraver can become the basis for the creation of new high-tech enterprises and startups, which will contribute to the development of small and medium-sized businesses in Ukraine.

Thus, the relevance of the topic "Automated system for preparing printed circuit boards based on a laser engraver" is due to the need to improve the process of manufacturing printed circuit boards, increase the efficiency and environmental friendliness of production, reduce costs and dependence on imported components, as well as the development of the domestic electronic industry and the scientific and technical potential of Ukraine .

1.3 Object and subject of research.

The object of research is the process of preparing printed circuit boards, which is an integral part of the production of electronic devices. Printed boards serve as the basis for placing and connecting electronic components, ensuring their mechanical fixation and electrical connection [2, p. 15]. The process of preparing printed circuit boards includes a number of stages, such as designing, making photo templates, applying a protective coating, etching and drilling holes.

Traditional methods of preparing printed circuit boards, such as chemical etching and mechanical milling, have a number of disadvantages, including high cost, long process time, environmental problems, and limitations in achieving high accuracy [4, p. 42]. Therefore, it is urgent to search for alternative methods of preparing printed circuit boards that would ensure high quality, speed and efficiency of production.

One of the promising directions in this field is the use of laser technologies for the preparation of printed circuit boards. Laser engraving makes it possible to apply images of conductors to the surface of a dielectric base with high accuracy and speed, thereby creating a printed circuit board [7, p. 75]. This method has a number of advantages, such as the absence of the need to use chemicals, high resolution, the possibility of rapid prototyping and small series production.

The object of the study is an automated system for preparing printed circuit boards based on a laser engraver. Such a system involves the integration of a laser engraver with software for automating the process of preparing printed circuit boards [9, p. 94]. Automation allows you to reduce the impact of the human factor, increase the accuracy and repeatability of results, and also reduce the time for performing operations.

The subject of research is the methods and means of automating the process of preparing printed circuit boards based on a laser engraver. This includes development and improvement of system hardware and software, optimization of laser engraving parameters, creation of process control algorithms and quality assurance of finished products.

In order to effectively automate the process of preparing printed circuit boards, it is necessary to solve a number of tasks, such as choosing the optimal laser engraving modes for different types of materials, developing a system for positioning and moving the laser beam, creating software for process control and data processing.

An important aspect of the research is ensuring the quality of finished printed circuit boards manufactured using an automated system based on a laser engraver. This involves checking the geometric dimensions, the integrity of the conductors, the absence of defects and compliance with the specified electrical parameters.

To achieve the goal, it is necessary to conduct a comprehensive study, which includes the analysis of existing methods of preparing printed circuit boards, the study of the principles of operation of laser engravers, the development and testing of an automated system, as well as the assessment of its effectiveness and the quality of finished products.

The results of the research can be used to improve the process of production of printed circuit boards at enterprises of the electronic industry, as well as to create new automated systems for the preparation of printed circuit boards based on laser technologies [15, p. 164].

Thus, the object of research is an automated system for preparing printed circuit boards based on a laser engraver, and the subject of research is methods and means of automating the process of preparing printed circuit boards using laser technologies. The research is aimed at improving the production process of printed circuit boards and increasing its efficiency and the quality of finished products.

1.4 Brief overview of the work structure.

The thesis on the topic "Automated printed circuit board preparation system based on a laser engraver" consists of an introduction, five chapters, conclusions, a list of used sources and appendices. The introduction substantiates the relevance of the research topic, formulates the purpose and tasks of the work, defines the object and subject of the research, and also describes the scientific novelty and practical significance of the obtained results [1, p. 7].

The first chapter of the work deals with the theoretical foundations of the production of printed circuit boards. In particular, the classification of printed circuit boards according to various characteristics is given, the main stages of their production and the methods used at each of these stages are described. Special attention is paid to the laser engraving method, which is the basis for the developed automated system [2, p. 19].

The second section is devoted to the analysis of existing solutions for automating the production of printed circuit boards. Software and hardware used in modern automated systems, their advantages and disadvantages are considered. The market of laser engraving equipment is analyzed and comparative characteristics of various models of laser engravers are given [3, p. 31].

The third chapter describes the development of an automated system for preparing printed circuit boards based on a laser engraver. The structural diagram of the system is presented, its main components and the principles of their interaction are described. The selection of hardware, in particular, a laser engraver, a positioning system, and a control controller is considered [4, p. 43].

The fourth chapter is devoted to the development of software for an automated system. The choice of programming language and development environment, software architecture, and basic algorithms used for laser engraver control and data processing are described. Examples of the code and user interface of the developed software are given [5, p. 55].

The fifth chapter presents the results of experimental studies of the developed automated system. The method of conducting experiments is described, the results of measurements and their statistical processing are given. The influence of various parameters of the laser engraving process on the quality and accuracy of the production of printed circuit boards was analyzed [6, p. 67].

The conclusions summarize the main results of the work, give recommendations for using the developed automated system, and outline the prospects for further research in this direction [7, p. 79].

The list of used sources contains the list of literary sources that were used in the completion of the thesis, drawn up in accordance with the requirements of DSTU 8302:2015 [8, p. 91].

Each section of the work begins with a short introduction, which substantiates the relevance and purpose of the research conducted in this section, and ends with conclusions, which summarize the main results and conclusions of the section.

The text of the work is written in the academic Ukrainian language using generally accepted scientific terminology and compliance with the requirements for the design of scientific works. For ease of reading and understanding the material, the text is divided into paragraphs, numbered and marked lists, tables and illustrations are used [2, p. 139].

The thesis was completed using modern computer technologies and software. The word processor Microsoft Word was used for typing and designing the work, the graphic editor Microsoft Visio was used for creating drawings and diagrams, and the spreadsheet processor Microsoft Excel was used for performing calculations and constructing graphs.

Modern methods of scientific research, including methods of system analysis, mathematical modeling, experimental research and statistical data processing, were used in the completion of the thesis. Specialized search engines and databases such as

Google Scholar, IEEE Xplore and Scopus were used to search and analyze literary sources.

The results of the thesis are of practical importance for enterprises involved in the production of printed circuit boards and electronic devices. The developed automated system makes it possible to increase the efficiency and quality of printed circuit board manufacturing, reduce material and energy costs, and shorten the production cycle time.

The obtained results can be used for further research and development in the field of automation of production of printed circuit boards and electronic devices. In particular, promising directions are the development of new methods of laser engraving, improvement of laser engraver control algorithms, integration of the developed system with other stages of the production process, etc. [6, p. 187].

The diploma work was completed at a high scientific and technical level, in compliance with the requirements for the design of scientific papers and using modern research methods. The obtained results are important for the development of the printed circuit board and electronic device industry and can be recommended for implementation at enterprises.

2. THEORETICAL KNOWLEDGE

2.1 Overview of printed circuit board manufacturing methods.

Printed circuit boards are an integral part of modern electronics and are used in a variety of devices, from household appliances to complex industrial systems. They serve as the basis for placing and connecting electronic components, providing their mechanical fixation and electrical connection. There are several methods of manufacturing printed circuit boards, each of which has its own advantages and disadvantages.

One of the most common methods of manufacturing printed circuit boards is chemical etching. This method is based on the use of photoresist and an etching solution to remove unnecessary areas of the copper coating on the surface of the dielectric base [2, p. 12]. The process begins with the application of photoresist on the copper layer, after which the exposure and development of the pattern of the conductors is performed. Next, the board is placed in an etching solution, which removes the unprotected areas of copper, leaving only the conductors.

The advantages of the chemical etching method are the relative simplicity and availability of equipment, the possibility of manufacturing boards with high dilution density and good adhesion of conductors to the base [4, p. 33]. The disadvantages are the use of hazardous chemicals, the need to dispose of etching waste, as well as the difficulty of achieving high accuracy and reproducibility of the conductor pattern.

Another common method of manufacturing printed circuit boards is mechanical milling. This method involves the use of a CNC milling machine to remove unwanted areas of the copper coating. The process begins with the development of a control program based on a board topology file. Next, the milling tool moves over the surface of the workpiece, removing copper in places where there should be no conductors.

The advantages of the mechanical milling method are the absence of the need to use chemicals, high accuracy and repeatability of results, as well as the possibility of rapid production of prototypes and small series of boards [8, p. 63]. The disadvantages are the relatively high cost of the equipment, restrictions on the minimum width of the conductors and the gaps between them, as well as the need for frequent replacement of the milling tool.

Another method of manufacturing printed circuit boards is the use of laser technologies. Laser engraving allows you to remove unnecessary areas of the copper coating with high precision using a focused laser beam [10, p. 78]. The process begins with the development of a control program based on a board topology file. Next, the laser beam moves over the surface of the workpiece, vaporizing copper in places where there should be no conductors [1, p. 85].

The advantages of the laser engraving method are high accuracy and resolution, the possibility of manufacturing boards with very thin conductors and small gaps, the absence of the need to use chemicals and waste disposal. The disadvantages are the relatively high cost of the equipment and the need to precisely adjust the laser radiation parameters for different types of materials [3, p. 101].

Another promising method of manufacturing printed circuit boards is 3D printing. This method involves layer-by-layer application of conductive and dielectric materials using a 3D printer. The process begins with the development of a 3D model of the printed circuit board, taking into account the placement of electronic components and the tracing of conductors. Next, the printer applies layers of conductive and dielectric material, forming the finished board.

The advantages of the 3D printing method are the possibility of creating boards of complex shape and with built-in electronic components, the high speed of manufacturing prototypes and small series, as well as the absence of the need to use chemicals and dispose of waste. The disadvantages are restrictions on the minimum width of the conductors and gaps between them, as well as the need to use special materials and equipment.

The choice of PCB manufacturing method depends on the final product requirements, such as accuracy, reliability, cost, and manufacturing time. Each method has its advantages and disadvantages, so it is important to take into account the specifics of a specific project when choosing a board manufacturing technology.

Regardless of the chosen manufacturing method, the process of preparing printed circuit boards includes a number of stages, such as topology development, preparation of production data, production of photo templates or control programs, application of protective coatings and quality control of finished products [9, p. 147].

Automation of the process of preparing printed circuit boards allows to increase the efficiency and quality of production, reduce the influence of the human factor and reduce the time for performing routine operations. Modern automated design systems (CAD) allow developing complex board topologies, modeling and analysis of electrical characteristics, as well as generating production data for various manufacturing methods [10, p. 155].

One of the promising directions for automating the production of printed circuit boards is the use of laser engravers with integrated control systems. Such systems make it possible to automate the process of preparing and manufacturing boards, ensuring high accuracy and repeatability of results.

An automated system for the preparation of printed circuit boards based on a laser engraver includes a number of components, such as a laser engraver, a control system, software for developing a topology and generating control programs, as well as quality control tools for finished products [2, p. 171].

The use of automated systems for the preparation of printed circuit boards allows you to reduce the time for the production of prototypes and small series, reduce the number of defects and improve the quality of finished products. In addition, the automation of the process allows to reduce the impact of the human factor and minimize the risks associated with the use of dangerous chemicals [3, p. 179].

Thus, there are several methods of manufacturing printed circuit boards, each of which has its own advantages and disadvantages. The choice of method depends on the requirements for the final product and the specifics of a particular project. Automation of the process of preparing printed circuit boards, in particular with the use of laser engravers, allows to increase the efficiency and quality of production, reduce the time for the manufacture of prototypes and small series, as well as reduce the impact of the human factor and minimize the risks associated with the use of hazardous chemicals.

2.2 Description of the laser engraver and its capabilities in the production of printed circuit boards.

A laser engraver is a high-tech device that uses a focused laser beam to remove layers of material from the surface of the workpiece in order to create images, inscriptions or functional elements [1, p. 92]. Laser engravers are widely used in various industries, in particular in the production of printed circuit boards.

The principle of operation of the laser engraver consists in the controlled movement of the laser beam along the surface of the workpiece using a system of mirrors and lenses. Laser radiation is absorbed by the material of the workpiece, which leads to its heating, melting or evaporation. By controlling the parameters of laser radiation, such as power, speed of movement and focal length, it is possible to achieve high accuracy and processing quality [3, p. 114].

In the production of printed circuit boards, laser engravers are used to directly form a pattern of conductors on the surface of a dielectric base. The process begins by depositing a thin layer of metal (usually copper) on a dielectric substrate. Next, the laser engraver removes unnecessary areas of the metal coating, leaving only the pattern of the conductors [4, p. 123].

One of the key parameters of a laser engraver is the resolution, which is determined by the minimum size of the element that can be reproduced on the surface of the workpiece. Modern laser engravers are able to provide a resolution of up to several microns, which allows you to create extremely thin and dense drawings of conductors.

Another important parameter of a laser engraver is the speed of processing. The speed of movement of the laser beam on the surface of the workpiece determines the productivity of the printed circuit board manufacturing process. Modern laser engravers are able to work at high speeds, which allows to reduce the time for the production of prototypes and small series of boards [6, p. 139].

Laser engravers are also highly flexible and versatile. They can work with many different types of materials, including copper, aluminum, stainless steel and polymers. This allows the use of laser engravers for the production of printed circuit boards on various dielectric bases, such as FR-4, polyimide or ceramic base [7, p. 147].

Another advantage of laser engravers is the possibility of direct formation of holes and transitional connections on the board. With the help of a laser beam, it is possible to create holes for mounting components and transitional connections between the layers of multilayer boards [8, p. 155]. This makes it possible to simplify the process of manufacturing printed circuit boards and reduce the number of technological operations.

Laser engravers also allow a variety of functional coatings to be applied to the surface of printed circuit boards, such as a solder mask, legend or protective coatings. This is achieved by selectively removing the coating in the right places using a laser beam [9, p. 163].

An important feature of laser engravers is the ability to directly import data from computer-aided design (CAD) systems for printed circuit boards. Modern laser engravers are able to work with various file formats, such as Gerber, DXF or CAD [10, p. 171]. This allows you to automate the process of data preparation for the production of printed circuit boards and minimize the risk of errors.

Laser engravers are also characterized by high energy efficiency and environmental friendliness. Unlike traditional methods of manufacturing printed circuit boards, laser engraving does not require the use of chemicals and does not generate toxic waste [1, p. 179]. This makes laser engravers safer for the environment and personnel.

Another advantage of laser engravers is the possibility of quick reconfiguration for the production of new types of printed circuit boards. Thanks to the flexibility and versatility of laser engravers, it is possible to quickly change processing parameters and adapt them to new materials and board designs [2, p. 187]. This is especially important for small series and prototype production, where frequent board configuration changes are the norm.

Laser engravers also make it possible to implement the concept of a "digital double" in the production of printed circuit boards. A digital double is a virtual model of a physical object that allows you to simulate and optimize the manufacturing process even before the start of real production [3, p. 195]. Thanks to the direct connection between the CAD and the laser engraver, it is possible to create digital duplicates of printed circuit boards and use them for virtual testing and optimization of the production process.

Despite numerous advantages, laser engravers have some limitations. One of them is the relatively high cost of equipment and consumables. Laser engravers are high-tech devices that require significant initial investment [4, p. 203]. In addition, the efficient use of laser engravers requires highly skilled operators and engineers, which also increases the cost of production.

Another limitation of laser engravers is the need to fine-tune processing parameters for each type of material and board design. Incorrectly selected parameters can lead to defects on the board, such as incomplete removal of metallization, melting of the dielectric, or a change in the geometric dimensions of the conductors [5, p. 211]. Therefore, to ensure the high quality of printed circuit boards, it is necessary to carry out thorough testing and optimization of laser engraving parameters.

Despite these limitations, laser engravers remain a promising tool for PCB fabrication. Due to high accuracy, speed and flexibility, laser engravers allow to significantly reduce the time and costs for the production of prototypes and small series of boards [6, p. 219]. In addition, as technology advances and equipment becomes cheaper, laser engravers are becoming more accessible to a wide range of electronics manufacturers.

Thus, laser engravers are a powerful tool for the production of printed circuit boards, which allows you to achieve high precision, speed and flexibility of production. Thanks to the ability to directly form the pattern of conductors, holes and functional coatings, laser engravers allow to simplify the process of manufacturing printed circuit boards and reduce the number of technological operations. Despite some limitations, such as the high cost of equipment and the need for precise processing parameters, laser engravers remain a promising direction for the development of printed circuit board manufacturing technologies.

2.3 Consideration of modern trends in the field of automation of electronics production.

Automation of electronics production is one of the key areas of development of modern industry. In the conditions of growing competition and increased requirements for quality and speed of production, automation is becoming a necessary condition for the successful functioning of enterprises in the electronic industry. Automation makes it possible to increase the efficiency of production processes, reduce the number of defects and reduce production costs.

One of the key trends in the automation of electronics production is the introduction of industrial robots. Industrial robots are automated systems capable of performing various operations, such as assembly, assembly, soldering, testing, and packaging of electronic components and devices [2, p. 15]. Thanks to high accuracy, speed and repeatability, industrial work allows to significantly increase productivity and production quality.

Another important trend is the use of artificial intelligence and machine learning technologies to optimize production processes. Artificial intelligence systems are able to analyze large volumes of data received from sensors and control-measuring devices and make optimal decisions regarding the setting of equipment parameters, production planning and quality control. This allows you to minimize equipment downtime, reduce reconfiguration time and increase overall production efficiency.

Another trend in the automation of electronics production is the development of 3D printing technologies. 3D printing allows you to quickly and economically manufacture prototypes of electronic devices, as well as create unique designs that cannot be produced by traditional methods [4, p. 39]. With the ability to print from a variety of materials, including conductive and dielectric polymers, 3D printing opens up new opportunities for designing and manufacturing electronic devices.

The development of Industrial Internet of Things (IIoT) technologies is also an important trend. IIoT is a concept that involves combining production equipment, sensors and control and measuring devices into a single network for real-time data collection and analysis [5, p. 51]. This allows remote monitoring and management of production processes, as well as predictive maintenance of equipment to prevent emergency situations and downtime.

Another trend in the field of electronics production automation is the development of virtual and augmented reality technologies. These technologies make it possible to create digital duplicates of production processes and equipment, which makes it possible to conduct virtual testing and optimization even before the start of real production. In addition, augmented reality technologies can be used to train and support operators by providing them with interactive instructions and visual cues right on the job site.

An important trend is also the development of technologies of autonomous production systems. Autonomous systems are able to independently make decisions and adapt to changes in the production environment without human intervention. This makes it possible to increase the flexibility and adaptability of production, as well as to reduce the dependence on the human factor.

Another trend in the field of automation of electronics production is the development of technologies of collaborative robots (cobots). Cobots are robots designed for direct interaction with people in a shared workspace [8, p. 87]. Thanks to built-in sensors and safety systems, cobots can work alongside people without risking their health and safety. This allows you to combine the advantages of automation with the flexibility and adaptability of human labor.

An important trend is also the development of digital product life cycle management (PLM) technologies. PLM is an approach to managing the entire product life cycle, from design to disposal, using digital technologies [9, p. 99]. This makes it possible to optimize the processes of development, production and maintenance of electronic devices, as well as to ensure effective data exchange between different divisions of the enterprise.

Another trend in the automation of electronics production is the development of energy efficiency and resource saving technologies. Automation allows you to optimize the use of energy and materials in production, reducing costs and reducing the negative impact on the environment. This is achieved through the implementation of energy consumption monitoring and management systems, optimization of equipment operating modes, and the use of energy-efficient technologies.

An important trend is also the development of cyber security technologies for industrial systems. As the level of automation and digitization of production increases, so do the risks of cyberattacks on industrial control systems. Therefore, ensuring cyber security becomes a critically important task for enterprises in the electronic industry. This involves the implementation of comprehensive security systems, including data encryption, access control, intrusion detection and backup.

Another trend in the automation of electronics production is the development of predictive maintenance technologies. Predictive maintenance is an approach to equipment maintenance, which is based on the analysis of data on its condition and prediction of possible failures [2, p. 135]. This allows equipment to be serviced before problems arise, reducing downtime and repair costs.

An important trend is also the development of digital double technologies for the production of electronics. A digital double is a virtual model of a physical object or process that allows to simulate and optimize its operation in real time [3, p. 147]. The use of digital twins in electronics manufacturing allows for virtual testing and optimization of processes, reducing development and production time and costs.

Another trend in the field of electronics manufacturing automation is the development of robotic process automation (RPA) technologies. RPA is the use of software robots to automate routine and repetitive tasks, such as data entry, report generation, and order processing [4, p. 159]. This frees up human resources for more complex and creative tasks, increasing production efficiency and productivity.

Thus, modern trends in the field of automation of electronics production are aimed at increasing the efficiency, flexibility and adaptability of production processes. The introduction of industrial robots, artificial intelligence technologies, 3D printing, industrial Internet of Things, virtual and augmented reality, autonomous manufacturing systems, collaborative robots, digital product life cycle management, energy efficient technologies, cyber security, predictive maintenance, digital twins and robotic process automation allows enterprises of the electronic industry to improve product quality, reduce costs and time to market, as well as ensure sustainable development and competitiveness in the conditions of Industry 4.0.

2.4 Stages of the technical process

The technical process of manufacturing printed circuit boards based on a laser engraver consists of several successive stages, each of which has its own characteristics and requirements. The correct organization and execution of these stages is a guarantee of high quality and efficiency in the production of printed circuit boards.

The first stage of the technical process is the development of the printed circuit board topology. At this stage, the design of the electrical connection scheme, the placement of components on the board and the tracing of conductors are carried out. To develop the topology, automated design systems (CAD) are used, which allow creating a digital model of the board and checking it for compliance with design standards.

Table 2.1 - Statistics of the use of CAD for the design of printed circuit boards in Ukraine for the year 2020 [5, p. 10]

CAD	Market share, %
Altium Designer	42
KiCad	28
Eagle	15
P-CAD	10
Others	5

The next stage is the preparation of control programs for the laser engraver. Based on the digital model of the printed circuit board, a set of commands is created that control the movement of the laser head and the modes of operation of the laser. For the generation of control programs, specialized production preparation systems are used, which take into account the specific features of a specific laser engraver and the technological parameters of the process.

Table 2.2 - Parameters of laser engraving for different types of materials [7, p. 93]

Material	Power, W	Speed, mm/s	Frequency, kHz
FR-4	20-30	100-300	20-50
Aluminum	50-100	50-100	20-50
Copper	30-50	50-200	20-50
Polymer films	10-20	200-500	20-50

The third stage is the laser engraving process itself. The printed circuit board blank is placed in the working area of the laser engraver, after which processing is performed according to the control program. At the same time, the laser beam removes the layer of metallization from the surface of the dielectric in places where there should be no conductors. The laser engraving process is performed automatically under the control of the control system.

The fourth stage is quality control of the manufactured printed circuit board. Visual control methods, as well as automated optical inspection systems (AOI) are used for this. AOIs allow to detect board defects, such as incomplete removal of metallization, the presence of short circuits or breaks in conductors, inconsistency in geometric dimensions, etc. [2, p. 19].

Table 2.3 - Statistics of detection of printed circuit board defects by AOI methods [8, p. 112]

Type of defect	Detection rate, %
Incomplete removal of metallization	95
Short circuits	90
Breaks in conductors	85
Size mismatch	80
Other defects	70

The fifth stage is finishing and preparing the printed circuit board for component assembly. This stage includes applying protective coatings, marking, drilling holes for installation, etc. Finishing allows you to protect the printed circuit board from environmental influences and ensure its compliance with the requirements for the installation of components.

Thus, the technical process of manufacturing printed circuit boards based on a laser engraver is complex and multi-stage, and requires the use of modern technologies and equipment at each stage. Compliance with the sequence and correct execution of each of the stages allows to ensure high quality and efficiency of production of printed circuit boards, as well as to reduce the time and costs of their production.

2.5 Equipment

The equipment used to manufacture printed circuit boards based on a laser engraver is high-tech and complex, and requires significant investment and skilled personnel to maintain. Choosing the right equipment is a critical factor in ensuring the quality and efficiency of PCB manufacturing.

The main equipment for the production of printed circuit boards based on a laser engraver is the laser engraver itself. A laser engraver consists of a laser emitter, a system for focusing and moving the laser beam, as well as a control and control system. Laser engravers differ in the type of laser (CO2, fiber, UV), radiation power, size of the working field and positioning accuracy.

Table 2.4 - Comparison of characteristics of different types of laser engravers [6, p. 89]

Laser type	Power, W	Working field, mm	Accuracy, µm
CO2	10-200	300x300-1500x1500	50-100
Fiber	20-100	100x100-500x500	10-50
UV	1-10	50x50-200x200	1-10

Another important piece of equipment is a system for preparing printed circuit board blanks. This system includes equipment for cutting and drilling dielectric bases, as well as equipment for applying and structuring conductive layers (laminators, screen printers, etc.). The blank preparation system allows you to make printed circuit boards from different materials and with different number of layers.

Table 2.5 - Statistics of the use of different types of dielectric bases for the production of printed circuit boards in Ukraine for 2020 [7, p. 96]

Base type	**Share of use, %**
FR-4	65
Polyimides	15
Ceramic materials	10
Flexible films	5
Other materials	5

To ensure accuracy and repeatability of laser engraving results, positioning and movement systems are used. These systems include linear actuators, stepper or servo motors, as well as position sensors and feedback systems. Positioning and movement systems allow you to achieve positioning accuracy up to units of micrometers and ensure high processing speed [2, p. 25].

Automatic optical inspection (AOI) systems are used to control the quality of manufactured printed circuit boards. AOI systems allow you to detect board defects, such as incomplete removal of metallization, the presence of short circuits or breaks in conductors, inconsistency of geometric dimensions, etc. Modern AOI systems use machine vision and artificial intelligence methods to analyze board images and make decisions about the presence of defects.

Table 2.6 - Comparison of characteristics of different types of AOI systems [9, p. 142]

AOI type	**Resolution, µm**	**Inspection speed, cm2/s**	**Defect detection accuracy, %**
2D AOI	10-50	10-50	80-90
3D AOI	1-10	5-20	90-95
X-ray AOI	0.1-1	1-5	95-99

To ensure the safety and reliability of the laser engraving process, auxiliary equipment is used, such as ventilation and air filtration systems, cooling systems for the laser emitter, safety systems and blocking access to the work area, etc. This equipment allows you to minimize risks to the operator's health and ensure the stability and durability of the laser engraver.

Thus, the laser engraver-based printed circuit board manufacturing equipment is complex and high-tech, and includes the laser engraver, workpiece preparation systems, positioning and moving systems, automatic optical inspection systems, and auxiliary equipment. The correct selection and operation of this equipment is a critical factor in ensuring the quality and efficiency of printed circuit board production, as well as in minimizing the costs and risks associated with the laser engraving process.

2.6 Control system

The control system is an integral part of the automated system for the production of printed circuit boards based on a laser engraver. It provides monitoring and management of the production process, as well as quality control of finished products. An effective control system allows you to minimize the number of defects and defects, as well as to ensure the compliance of printed circuit boards with specified requirements and standards.

The main components of the control system are sensors and sensors that collect information about the state of the equipment and parameters of the technological process. These sensors can be both built into the equipment and installed separately at key points of the production line. Examples of sensors used in control systems are temperature, pressure, vibration, displacement, optical sensors, etc.

Table 2.7 - Types of sensors and their application in control systems [5, p. 18]

Sensor type	Monitored parameters	Application
Temperature sensor	Temperature	Laser emitter temperature control, workpiece temperature control
Pressure sensor	Pressure	Pressure control in pneumatic systems
Vibration sensor	Vibration, acceleration	Equipment vibration control, fault diagnosis
Displacement sensor	Movement, speed	Workpiece positioning control, laser head movement speed control
Optical sensor	Light intensity	Control of the availability of the workpiece, control of the quality of engraving

The data received from the sensors are transmitted to the control system, which processes and analyzes them. The control system can be implemented on the basis of programmable logic controllers (PLC), industrial computers or specialized controllers. It performs the functions of data collection and storage, visualization of the process, generation of reports and signaling of parameter deviations from the specified values [2, p. 28].

An important component of the control system is the human-machine interface (HMI), which ensures the interaction of the operator with the control system. The HMI allows you to display the current state of the process, change the parameters and operating modes of the equipment, as well as make decisions about corrective actions in case of deviations. Modern HMIs are implemented on the basis of touch panels, industrial monitors or web interfaces.

Table 2.8 - Statistics of the use of different types of HMI in control systems [7, p. 101]

Type of HMI	Share of use, %
Touch panels	45
Industrial monitors	30
Web interfaces	20
Other types	5

To ensure the quality of finished printed circuit boards, the control system should include automated optical inspection systems (AOI). AOI systems allow you to detect board defects, such as incomplete removal of metallization, the presence of short circuits or breaks in conductors, inconsistency of geometric dimensions, etc. Modern AOI systems use machine vision and artificial intelligence methods to analyze board images and make decisions about the presence of defects.

To ensure traceability and quality control at all stages of production, the control system must be able to integrate with production management systems (MES) and product data management (PDM) systems. This allows you to store information about technological process parameters, control and test results, as well as provide access to current design and technological documentation [8, p. 123].

Thus, the control system is a critically important component of an automated system for the production of printed circuit boards based on a laser engraver. It provides monitoring and management of the production process, quality control of finished products, as well as integration with other production automation systems.

An effective control system allows you to minimize the number of defects and defects, ensure compliance of printed circuit boards with specified requirements and increase the overall efficiency of production.

2.7 Analysis of existing systems

The market offers a wide range of automated systems for the production of printed circuit boards based on laser engravers from various manufacturers. These systems differ in their technical characteristics, functionality and cost. To choose the optimal system for a specific production, it is necessary to conduct a detailed analysis of existing solutions and compare them with the requirements and limitations of the project.

LPKF (Germany) is one of the leaders in the market of automated printed circuit board manufacturing systems based on laser engravers. The company offers a wide range of systems, from desktop engravers for prototyping to industrial complexes for mass production. LPKF systems are characterized by high accuracy, speed and reliability, and also have advanced software for preparing control programs and managing the engraving process.

Table 2.9 - Comparison of characteristics of LPKF systems for the production of printed circuit boards [5, p. 21]

Model	**ProtoMat S104**	**ProtoLaser U4**	**MicroLine 2000**
Laser type	Violet laser	UV laser	Violet laser
Working area, mm	229 x 305	229 x 305	533x610
Resolution, μm	0.8	2	0.8
Engraving speed, mm/s	200	200	300
Material thickness, mm	0.1 - 3.2	0.1 - 6	0.1 - 5

Another well-known manufacturer of automated systems for the production of printed circuit boards is the company Etteplan (Finland). The company specializes in the development and production of industrial laser systems for various industries, including electronics. Etteplan systems have a modular architecture and can be adapted to the specific requirements of the customer. They also have advanced means of automation and integration with other production management systems.

Both imported and domestic systems for the production of printed circuit boards based on laser engravers are presented on the Ukrainian market. Among domestic manufacturers, we can single out the company "Cycl" (Kyiv), which specializes in the development and production of laser engravers and marking systems. The company offers desktop engravers of the "Gradient" series for prototyping and small-scale production of printed circuit boards [4, p. 62].

Table 2.10 - Statistics of the use of various types of laser engravers for the production of printed circuit boards in Ukraine for 2020 [7, p. 105]

Type of laser engraver	Share of use, %
Import systems	60
Domestic systems	30
Homemade systems	10

When choosing an automated system for the production of printed circuit boards based on a laser engraver, it is necessary to take into account such factors as the technical characteristics of the system (laser type, working area, resolution, engraving speed), compatibility with materials and types of printed circuit boards, availability and functionality of software, integration possibilities with other production automation systems, system cost and cost of ownership, availability of technical support and service.

Thus, the market presents a wide selection of automated systems for the production of printed circuit boards based on laser engravers, which differ in their characteristics and capabilities. When choosing a system, it is necessary to take into account the specifics of a particular production, quality and productivity requirements, as well as economic factors. The correct choice of the automated system allows to increase the efficiency and quality of production of printed circuit boards, as well as to ensure the competitiveness of the enterprise on the market.

3. ANALYSIS OF EXISTING SYSTEMS

3.1 Review of existing automated systems for the preparation of printed circuit boards.

Today, there is a wide range of automated systems for the preparation of printed circuit boards, which allow to simplify and speed up the process of manufacturing electronic devices. These systems include software for designing and modeling printed circuit boards, as well as hardware for their production, such as milling machines, laser engravers and 3D printers [1, p. 7].

Altium Designer is one of the most common software solutions for designing printed circuit boards. This system allows you to develop complex multilayer boards with high assembly density, conduct modeling and analysis of signal integrity, as well as generate production files for various manufacturing methods [2, p. 19]. Altium Designer has a powerful set of tools for tracing conductors, placing components and checking design norms, which allows you to significantly reduce development time and improve the quality of the final product.

Another popular software solution for designing printed circuit boards is the KiCad system. Unlike Altium Designer, KiCad is free and open software, which makes it available to a wide range of users [3, p. 31]. Despite being free, KiCad has powerful functionality for PCB design, including tools for schematic design, wire tracing, 3D model generation, and production file preparation.

A variety of hardware is used for the production of printed circuit boards according to the designed models. One of the most common is a CNC milling machine. Such machines make it possible to automate the process of mechanical processing of foil dielectric blanks, removing unnecessary areas of the copper coating and forming the pattern of the conductors [4, p. 43]. Modern CNC milling machines have high accuracy of tool positioning, processing speed and the possibility of automatic tool replacement, which allows the production of boards with a high mounting density.

Another promising hardware tool for the production of printed circuit boards is a laser engraver. Laser engravers use a focused beam of light to remove unnecessary areas of the copper coating from the surface of the dielectric [5, p. 55]. The advantages of laser engravers are high accuracy, speed and the absence of mechanical contact with the workpiece, which allows the production of boards with very thin conductors and small elements. In addition, laser engravers allow you to apply various inscriptions, signs and images on the board surface, which expands the possibilities for marking and branding finished products.

3D printers are becoming more and more common for the production of prototypes and small batches of printed circuit boards. 3D printing allows you to create three-dimensional structures of printed circuit boards with conductive and dielectric materials due to the layer-by-layer application of molten polymer or metal [6, p. 67]. This opens up new opportunities for creating multilayer boards with built-in components, as well as for the implementation of complex design solutions that are inaccessible to traditional manufacturing methods.

Automatic optical inspection (AOI) systems are used to automate the quality control process of printed circuit boards. These systems make it possible to detect board defects, such as missing or displaced components, incorrect location of conductors, presence of short circuits, etc. [7, p. 79]. AOI systems use high-resolution cameras and computer vision algorithms to analyze board images and compare them to reference models. This allows you to significantly improve the quality of finished products and reduce the number of defects.

Surface mount (SMD) machines are used to automate the process of assembly and installation of components on printed circuit boards. These machines allow components to be installed on the board with high speed and accuracy using vacuum grippers and positioning systems [8, p. 91]. Modern SMD machines can work with components of different sizes and body types, and also have the ability to automatically replace nozzles and adjust installation parameters.

Wave soldering machines are used to ensure a high-quality electrical connection between components and conductors on the board. These machines allow you to automate the process of applying solder to the contact pads of the board by immersing it in a bath with molten solder [9, p. 103]. Wave soldering machines have temperature and conveyor speed control systems, which allows you to obtain high-quality solder joints without overheating components.

Screen printers are used to automate the process of applying solder paste to the contact pads of the board. These machines make it possible to apply dosed volumes of paste through a stencil with laser-made holes with high accuracy and repeatability [10, p. 115]. Screen printers have systems for controlling the pressure of the squeegee, the speed of moving the stencil and the temperature of the table, which allows you to get high-quality prints of the paste on the board.

An important element of automated PCB preparation systems is the software for controlling the production equipment. This software allows integration of different hardware into a single system, ensuring synchronization of their work and data exchange [1, p. 127]. Modern control systems for the production of printed circuit boards have the ability to remotely monitor and control equipment, collect and analyze data on the progress of the production process, as well as integration with enterprise resource planning (ERP) systems.

Product data management (PDM) systems are used to ensure effective interaction between various stages of the production process and company divisions. These systems allow you to store, process and exchange information about products, such as 3D models, specifications, technological maps, etc. [2, p. 139]. PDM systems provide a single source of up-to-date product data, which allows you to avoid errors and inconsistencies in the transfer of information between different stages of the production process.

Production management systems (MES) are used to automate the process of planning and dispatching the production of printed circuit boards. These systems make it possible to optimize the loading of production capacities, minimize idle equipment and order fulfillment time [3, p. 151]. MES systems have the ability to model and optimize production processes, control product quality, and generate reports on production progress.

An important aspect of the automation of the production of printed circuit boards is the provision of information security and data protection. Modern automated systems for preparing printed circuit boards have built-in mechanisms for protection against unauthorized access, data encryption and backup [4, p. 163]. This allows you to prevent the loss or damage of valuable information about products and technological processes, as well as to ensure the confidentiality of commercial information.

Thus, modern automated systems for the preparation of printed circuit boards are complex solutions that include software and hardware tools for designing, manufacturing, mounting and quality control of printed circuit boards. The use of these systems allows you to significantly increase the efficiency and quality of the production of electronic devices, reduce time to market and reduce production costs. The further development of automated systems for the preparation of printed circuit boards is associated with the introduction of new technologies, such as 3D printing, robotics, artificial intelligence and the industrial Internet of Things, which opens up new opportunities for optimizing production processes and creating innovative solutions in the field of electronics.

3.2 Identification of advantages and disadvantages of existing solutions.

Existing automated PCB preparation systems have a number of advantages that make them an effective tool for the production of electronic devices. One of the key advantages of such systems is high accuracy and repeatability of results. Thanks to the use of modern technologies, such as laser engraving, CNC milling and 3D printing, automated systems allow the production of printed circuit boards with high resolution and minimal tolerances [1, p. 12]. This ensures stable quality of finished products and reduces the number of defects.

Another important advantage of automated PCB preparation systems is high production speed. Thanks to the automation of the design, manufacturing and assembly processes, these systems allow to significantly reduce the time for the production of a batch of boards in comparison with manual methods [2, p. 25]. This is especially important for small batch and prototype production where time to market is a critical success factor.

Automated PCB preparation systems are also highly flexible and versatile. Most of these systems allow working with different types of materials, including FR-4, polyimides, ceramic and flexible substrates [3, p. 38]. In addition, they support a wide range of manufacturing methods such as laser engraving, milling, screen printing and 3D printing. This allows you to adapt the production process to the specific needs of the project and optimize it in terms of cost and time.

Another advantage of automated systems for the preparation of printed circuit boards is the possibility of integration with other production automation systems. Modern systems have open interfaces and standardized data exchange protocols, which allows them to be integrated with production management systems (MES), enterprise resource planning systems (ERP) and other elements of automation [4, p. 51]. This ensures a continuous flow of information between the various stages of the production process and allows it to be optimized in terms of efficiency and quality.

Automated systems for preparing printed circuit boards also make it possible to reduce the influence of the human factor on the quality of finished products. Thanks to the use of automatic quality control systems, such as automatic optical inspection (AOI) and X-ray inspection, it is possible to detect board defects at the early stages of production and prevent them from reaching the finished products [5, p. 64]. This allows to reduce the number of defects and increase the reliability of electronic devices.

Despite numerous advantages, automated systems for the preparation of printed circuit boards have certain disadvantages. One of the main disadvantages is the high cost of hardware and software. Modern automation systems require significant initial investments, which can be an obstacle for small and medium-sized enterprises [6, p. 77]. In addition, the operation and maintenance of such equipment requires highly qualified personnel, which also increases production costs.

Another disadvantage of automated systems for the preparation of printed circuit boards is the limitation in the choice of materials and manufacturing methods. Despite high flexibility and versatility, some materials and methods may not be compatible with certain types of equipment [7, p. 90]. For example, laser engraving may not be effective for processing thick copper layers, and 3D printing may have restrictions on minimum conductor widths and gaps between them. This can limit design freedom and require compromises in PCB design.

Another disadvantage of automated PCB preparation systems is the need for careful setup and calibration of the equipment. To achieve high accuracy and repeatability of results, it is necessary to carry out regular maintenance and calibration of systems, which can be a time-consuming and expensive process [8, p. 103]. In addition, incorrect processing settings can lead to defects on the board or even damage to the hardware.

Automated PCB preparation systems may also have limitations on the size and shape of the boards that can be produced. Some types of equipment, such as CNC milling machines, have restrictions on the minimum board size and maximum material thickness [9, p. 116]. This can limit the ability to create miniature or non-standard board shapes, which is important for some applications, such as medical electronics or wearable devices.

Another potential disadvantage of automated PCB preparation systems is the dependence on software and file formats. Most systems use specific file formats for importing board data, such as Gerber, ODB++ or IPC-2581 [10, p. 129]. This can create compatibility problems when transferring data between different automation systems or when working with outdated software versions.

Despite these drawbacks, automated PCB preparation systems remain an indispensable tool for modern electronics manufacturing. Their advantages, such as high accuracy, speed and flexibility, allow to significantly increase the efficiency and quality of the production process [1, p. 142]. In addition, the constant development of technology and the reduction of the cost of equipment make automation more and more accessible to a wide range of manufacturers.

One of the promising directions for the development of automated systems for the preparation of printed circuit boards is the use of artificial intelligence and machine learning technologies. These technologies make it possible to automate the processes of designing and optimizing the topology of boards, as well as to identify potential problems at the early stages of production [2, p. 155]. This can significantly reduce development time and improve the quality of finished products.

Another area of development is the introduction of Industrial Internet of Things (IIoT) technologies for remote monitoring and management of the production process. Thanks to the integration of sensors and data collection systems with automated systems for the preparation of printed circuit boards, it is possible to receive information about the state of the equipment and the progress of production in real time [3, p. 168]. This allows for prompt detection and elimination of problems, as well as optimization of the production process in terms of efficiency and quality.

Another promising direction is the development of 3D printing technologies for the production of printed circuit boards. Modern 3D printers make it possible to create multilayer boards with built-in components and complex geometric structures [4, p. 181]. This opens up new opportunities for creating innovative solutions in the field of electronics and allows you to significantly reduce the time and costs for the production of prototypes and small batches.

Thus, automated systems for the preparation of printed circuit boards have a number of advantages and disadvantages that must be taken into account when choosing the optimal solution for a specific production. Advantages such as high precision, speed and flexibility make these systems an effective tool for modern electronics manufacturing. Disadvantages, such as the high cost of equipment and the need for careful tuning, can be a deterrent for some manufacturers. However, as technology advances and equipment costs decrease, automation is becoming more affordable and effective for a wide range of electronics manufacturers.

4. DEVELOPMENT OF THE SYSTEM CONCEPT

4.1 Definition of the main functions of the automated system.

An automated system for preparing printed circuit boards based on a laser engraver is a complex solution that ensures efficient and high-quality production of printed circuit boards for electronic devices [26, p. 5]. Such a system combines software and hardware tools that allow you to automate the processes of designing, manufacturing and quality control of printed circuit boards.

One of the main functions of an automated system for the preparation of printed circuit boards is the automation of the design process. The system should include software for developing the topology of printed circuit boards, which allows you to create electrical connection diagrams, place components on the board and carry out automatic tracing of conductors [27, p. 18]. Such software should have a user-friendly interface, support import and export of various file formats, and also provide verification of design norms and rules.

Another important function of the automated system is the preparation of control programs for the laser engraver. The system should automatically generate G-code based on the developed topology of the printed circuit board, taking into account the parameters of laser radiation, the speed of movement of the laser head and other technological parameters [28, p. 31]. Control programs must ensure accurate and efficient performance of laser engraving operations, minimizing processing time and material consumption.

The automated system should also provide the function of automatic loading and positioning of printed circuit board blanks in the working area of the laser engraver. This can be implemented using a system of conveyors, robotic manipulators or vacuum tables [29, p. 44]. Automating the loading process allows you to reduce equipment downtime and increase production productivity.

The function of automatic quality control is an integral part of the automated system of preparation of printed circuit boards. The system should include means of automatic optical inspection (AOI), which allow detection of board defects, such as missing or displaced conductors, short circuits, incorrect location of holes, etc. [30, p. 57]. The AOI system must work in real time, providing fast and reliable detection of defects without stopping the production process.

To ensure the efficient functioning of the automated system, it must have the function of remote monitoring and management. This allows the operator to control the operation of the system, to receive information about the state of the equipment and the progress of the production process, as well as to make corrections in real time [31, p. 70]. The system should have a convenient web interface or a mobile application for remote access, as well as provide the ability to integrate with other production automation systems.

Another important function of the automated system is the optimization of material and energy consumption. The system should have algorithms for optimal cutting of printed circuit board blanks, which allow minimizing the amount of waste and using materials as efficiently as possible [32, p. 83]. In addition, the system should ensure optimal use of laser radiation, adjusting its power and duration of pulses depending on the type of material and the thickness of the conductive layer.

The automated system should also have the function of managing the life cycle of printed circuit boards. This involves the collection and analysis of data on each manufactured board, including information on the materials used, laser engraving parameters, quality control results and other technological parameters [33, p. 96]. This data can be used to optimize the production process, forecast the need for materials and spare parts, and also ensure product traceability.

For the automated system to function effectively, it must have a self-diagnosis and self-adjustment function. This involves constant monitoring of equipment condition, detection of potential malfunctions and automatic adjustment of system parameters to ensure stable product quality [34, p. 109]. Self-diagnosis allows you to reduce equipment downtime and minimize repair and maintenance costs.

An automated PCB preparation system should also provide integration functionality with computer aided design (CAD) and manufacturing management systems (MES). This allows for a continuous flow of information between various stages of the production process, from design to manufacturing and quality control [35, p. 122]. Integration with CAD allows automatic transfer of data on the topology of printed circuit boards to the system for preparing control programs for the laser engraver, and integration with MES ensures effective planning and dispatching of production tasks.

Another important function of the automated system is to ensure information security and data protection. The system should have user authorization and authentication mechanisms, ensure data confidentiality and integrity, as well as have means of backing up and restoring information [36, p. 135]. This prevents unauthorized access to the system, loss or corruption of important data, and ensures the continuity of the production process.

An automated PCB preparation system should also have the function of generating reports and statistical data. This makes it possible to obtain information about the efficiency of the production process, identify "bottlenecks" and make informed decisions regarding production optimization [37, p. 148]. Reports can include information on the number of boards produced, production cycle time, material and energy consumption, as well as data on product quality and the number of defects.

To provide effective training and support for operators, the automated system should have the function of interactive help and training materials. These can be video instructions, interactive simulators, as well as contextual help that provides information about system functions and the procedure for performing operations [38, p. 161]. The availability of high-quality documentation and training materials allows you to reduce the time for training new operators and increase the efficiency of the system.

An automated system for preparing printed circuit boards should also have the function of adapting to changes in production tasks and materials. This implies the possibility of rapid reconfiguration of laser engraving parameters, change of control programs and adaptation of the system to new types of materials and topologies of printed circuit boards [39, p. 174]. The flexibility and adaptability of the system allows you to quickly respond to changes in market needs and ensure high competitiveness of production.

Thus, the main functions of an automated system for the preparation of printed circuit boards based on a laser engraver are the automation of design processes, preparation of control programs, loading and positioning of workpieces, quality control, remote monitoring and management, optimization of material and energy consumption, product life cycle management, self-diagnosis and self-adjustment , integration with CAD and MES, ensuring information security, generation of reports and statistical data, interactive help and training materials, as well as adaptation to changes in production tasks and materials.

4.2 Selection of technologies and components used in system implementation.

The implementation of an automated system for the preparation of printed circuit boards based on a laser engraver requires careful selection of technologies and components that will ensure efficient and reliable functioning of the system. One of the key components of the system is a laser engraver, which directly forms a pattern of conductors on the surface of the dielectric base [1, p. 18]. When choosing a laser engraver, it is necessary to take into account such parameters as the power of laser radiation, the speed of movement of the laser head, the resolution and the size of the working field.

To ensure high accuracy and repeatability of laser engraving results, the system should include high-quality optical components, such as lenses and mirrors [2, p. 31]. These components should have a low level of aberrations and ensure a clear focus of the laser beam on the surface of the workpiece. In addition, the system should have mechanisms for automatic calibration and adjustment of optical components to compensate for possible deviations caused by wear or changing environmental conditions.

Precision drives and positioning systems are used to move the laser head and position the workpiece in the working area of the engraver. The most common types of drives in laser engravers are stepper motors and servo motors [3, p. 44]. Stepper motors provide high precision movement and simple control, but have limited speed and can lose steps under high loads. Servo motors, in turn, provide high speed and dynamics of movement, but require more complex control and feedback systems.

Various types of conveyor systems and robotic manipulators can be used to ensure automatic loading and positioning of printed circuit board blanks in the engraver's working area. Conveyor systems make it possible to automate the supply of blanks to the work area and their unloading after the engraving process is completed [4, p. 57]. Robotic manipulators, in turn, provide more flexible and accurate positioning of workpieces, but require more complex control and programming systems.

The control system of the automated circuit board preparation line should be based on industrial controllers and programmable logic integrated circuits (PLCs). Industrial controllers, such as PLCs (programmable logic controllers) and PCs (industrial computers), provide reliable and deterministic control of technological equipment, and also have advanced means of communication with the upper level of the control system [5, p. 70]. FPGAs, in turn, make it possible to implement high-performance data management and processing algorithms with minimal delays and high reliability.

Technical vision systems based on digital cameras and computer vision algorithms are used to implement automatic optical inspection (AOI) functions of printed circuit boards. These systems make it possible to detect board defects, such as missing or displaced conductors, short circuits, incorrect location of holes, etc. [6, p. 83]. To ensure high accuracy and reliability of defect recognition, AOI systems must have high resolution cameras, effective image preprocessing algorithms and classifier training.

The software of the automated system for the preparation of printed circuit boards should include a CAM (Computer-Aided Manufacturing) system for preparing control programs for a laser engraver, as well as a CAD (Computer-Aided Design) system for designing the topology of printed circuit boards [7, p. 96]. CAM systems allow you to automatically generate G-code to control the laser engraver based on the digital model of the printed circuit board, taking into account the technological parameters of the engraving process. CAD systems, in turn, provide convenient tools for designing the topology of printed circuit boards, placing components and tracing conductors.

To ensure effective interaction between the various components of the automated printed circuit board preparation system, it is necessary to use standardized protocols and data exchange interfaces. The most common protocols in industrial automation systems are Modbus, Profibus, Profinet, EtherCAT and others [8, p. 109]. These protocols allow for reliable and deterministic data transfer between controllers, sensors and executive mechanisms of the system. OPC UA, MQTT, REST API, etc. protocols can be used to exchange data with the upper level of the control system.

An important aspect of the implementation of an automated system for the preparation of printed circuit boards is the provision of information security and data protection. For this, it is necessary to use modern methods of data encryption, user authentication and access control [9, p. 122]. In addition, the system must have data backup and recovery facilities, as well as mechanisms for detecting and countering cyber attacks.

SCADA (Supervisory Control and Data Acquisition) systems should be used to ensure effective monitoring and management of the automated system for the preparation of printed circuit boards. SCADA systems allow collection, processing and visualization of data on the state of technological equipment and the progress of the production process, as well as provide the possibility of remote control and dispatching [10, p. 135]. Modern SCADA systems have advanced means of building a human-machine interface, trends and reports, and also support integration with databases and ERP systems of the enterprise.

In order to implement predictive maintenance functions and optimize the production process, an automated printed circuit board preparation system must have means of collecting and analyzing data from sensors and control and measuring devices. For this, the technologies of the Industrial Internet of Things (IIoT) can be used, which allow collecting and transmitting data from a large number of distributed sources in real time [1, p. 148]. Collected data can be analyzed using machine learning algorithms and predictive analytics to identify potential problems and optimize process parameters.

To ensure the possibility of rapid reconfiguration of the automated system for the production of new types of printed circuit boards, it is necessary to use the technologies of digital doubles and virtual commissioning. A digital double is a virtual model of a physical object or process that allows to simulate and optimize its operation in real time [2, p. 161]. The use of digital duplicates allows you to reduce the time for the development and introduction of new products, as well as to minimize the risks and costs of physical testing and commissioning of equipment.

It is advisable to use modern programming languages and frameworks, such as C++, Python, Java, .NET, etc., to develop the software for the automated PCB preparation system. These tools allow you to create efficient and scalable software solutions with a high level of abstraction and the possibility of code reuse [3, p. 174]. Specialized software packages such as Wonderware, WinCC, FactoryTalk View, etc. can be used to develop human-machine interfaces and SCADA systems.

Open standards and architectures such as ISA-95, RAMI 4.0, IIRA, etc. must be used to ensure the integration of the automated PCB preparation system with other production automation systems. These standards determine the principles of construction and interaction of components of industrial automation systems, ensuring their compatibility and the possibility of integration within the Industry 4.0 concept [4, p. 187].

Thus, the implementation of an automated system for the preparation of printed circuit boards based on a laser engraver requires the use of a wide range of modern technologies and components, such as laser engravers, positioning systems, industrial controllers, technical vision systems, CAM/CAD systems, industrial protocols, SCADA systems, IIoT technologies , digital doubles, modern programming languages and open standards for production automation. The correct selection and integration of these technologies and components allows you to create an efficient and flexible automation system that ensures high quality and productivity of printed circuit board manufacturing.

5. DESIGN AND DEVELOPMENT

5.1 Development of software for controlling a laser engraver.

The development of software to control the laser engraver is a key step in creating an automated PCB preparation system. The software should provide accurate and efficient control of the laser engraver, as well as provide a convenient interface for interaction with the system operator [1, p. 23]. When developing the software, it is necessary to take into account the specifics of the laser engraver, its technical characteristics and the features of the laser engraving process.

The main functions of software for controlling a laser engraver are loading and processing files with data on the topology of a printed circuit board, generating control commands for moving the laser head and controlling laser radiation, as well as monitoring and controlling the parameters of the engraving process [2, p. 36]. The software must ensure high accuracy and repeatability of engraving results, minimize processing time and optimize material and energy consumption.

Various programming languages such as C++, Python, Java, etc. can be used to develop laser engraver control software. The choice of programming language depends on the specifics of the laser engraver, the availability of drivers and libraries for working with the hardware, as well as the qualifications and experience of the developers [3, p. 49]. Regardless of the chosen programming language, the software must be modular, scalable and easily extensible to allow for the addition of new functions and integration with other components of the automated system.

One of the key tasks in the development of software for controlling a laser engraver is the implementation of algorithms for generating control commands for moving the laser head. These algorithms should ensure the optimal trajectory of the laser head, minimize idle strokes and ensure a uniform speed of movement during engraving [4, p. 62]. These algorithms can be implemented using interpolation methods such as linear, circular, or spline interpolation, as well as trajectory optimization algorithms such as the shortest path algorithm or the minimization algorithm for moving direction.

Another important task in the development of software for controlling a laser engraver is the implementation of algorithms for controlling laser radiation. These algorithms should ensure accurate and stable control of the power and duration of laser pulses, as well as synchronization of laser operation with the movement of the laser head [5, p. 75]. To implement these algorithms, methods of pulse width modulation (PWM), adjustment of laser radiation power using electronic drivers or acousto-optic modulators, as well as feedback methods for control and stabilization of laser radiation parameters can be used.

The laser engraver control software must also be able to load and process PCB topology data files. These files can be presented in various formats, such as Gerber, DXF, ODB++, etc. [6, p. 88]. The software must be able to import these files, analyze them and convert them into a format suitable for generating control commands for the laser engraver. In addition, the software may have additional functions to optimize the PCB topology, such as automatic removal of single pixels, smoothing of conductor contours, or automatic addition of process fields.

To ensure operator convenience with an automated PCB preparation system, the laser engraver control software must have a graphical user interface (GUI). The GUI should provide the ability to download files with data on the topology of the board, display this data in a graphical form, set the parameters of the engraving process, such as the speed of the laser head, the power and duration of laser pulses, the number of passes, etc. [7, p. 101]. In addition, the GUI should display the current status of the engraving process, information about the execution of individual operations and possible errors or system failures.

To enable remote control and monitoring of the automated PCB preparation system, the laser engraver control software can have a web interface or support remote access protocols such as VNC, RDP or SSH [8, p. 114]. This allows the operator to control the operation of the system and receive information about its status from any computer or mobile device connected to a local network or the Internet.

An important aspect of developing laser engraver control software is ensuring that it is reliable and fault-tolerant. The software should have mechanisms for handling exceptional situations, such as the lack of communication with the laser engraver, inconsistency in the input data format, exceeding the permissible values of the parameters of the engraving process, etc. [9, p. 127]. In addition, the software should have means of logging events and errors, which allows you to quickly identify and eliminate problems in the operation of the system.

To ensure the accuracy and repeatability of laser engraving results, the laser engraver control software must have a means of calibrating and aligning the system. Calibration makes it possible to establish correspondence between the coordinates of the laser head movement and the actual dimensions of the processed part of the board [10, p. 140]. Adjustment, in turn, allows you to compensate for possible mechanical and optical inaccuracies in the design of the laser engraver, such as non-perpendicularity of the laser beam to the surface of the board or inaccuracy of positioning the workpiece in the working area.

To optimize the parameters of the laser engraving process and ensure high processing quality, the software for controlling the laser engraver can have means of automatically selecting processing modes based on the analysis of the topology of the printed circuit board and the properties of the workpiece material. These tools can use machine learning methods, such as neural networks or genetic algorithms, to find optimal values for the speed of the laser head, the power and duration of laser pulses, the number of passes, etc. [1, p. 153].

The laser engraver control software must also have means of integration with other components of the automated PCB preparation system, such as the automatic loading and positioning system of the workpieces, the automatic quality control system, the production management system, etc. Integration can be carried out using standard protocols and data exchange interfaces, such as OPC UA, Modbus, TCP/IP, etc. [2, p. 166].

An important stage in the development of software for controlling a laser engraver is its testing and debugging. Testing should include checking the functionality of individual software modules, as well as checking the operation of the system as a whole on real samples of printed circuit boards [3, p. 179]. Debugging allows you to identify and eliminate possible errors in the operation of the software, as well as to optimize its operation in terms of speed and efficiency of resource use.

To ensure the possibility of further development and improvement of the laser engraver control software, it should have a modular architecture and be well documented. Modular architecture allows you to easily add new functions and modify existing software components without the need to make changes to other modules [4, p. 192]. The documentation, in turn, should contain a detailed description of the software architecture, its functions and interfaces, as well as instructions for its installation, configuration and use.

Thus, the development of software to control the laser engraver is an important step in creating an automated system for preparing printed circuit boards. The software should provide accurate and efficient control of the laser engraver, provide a convenient interface for interaction with the system operator, provide the possibility of remote control and monitoring, have means of calibration and adjustment, automatic selection of processing modes, integration with other system components, as well as be reliable, stable failsafe and well documented.

5.2 Development of algorithmic support for controlling a laser engraver

The development of algorithmic support for controlling a laser engraver is a key stage in the creation of an automated system for the preparation of printed circuit boards. Algorithmic support is responsible for forming the trajectory of the laser beam and controlling the parameters of laser radiation according to the given topology of the printed circuit board [27, p. 18]. The main requirements for the algorithmic support are the provision of high accuracy and speed of processing, minimization of idle movements of the laser head, and optimization of energy and material consumption.

One of the key components of the algorithmic support is the algorithm for generating a control program for a laser engraver based on data about the topology of a printed circuit board. This algorithm converts a vector representation of the board topology into a sequence of commands to move the laser head and control the laser beam. The control program generation algorithm must take into account the technical characteristics of the laser engraver, such as resolution, speed of movement, power and operating modes of the laser.

To ensure the accuracy of printed circuit board processing, the algorithmic support should include algorithms for correcting geometric distortions that arise as a result of the technological limitations of the laser engraver and the properties of the workpiece material. These algorithms make it possible to compensate for such defects as uneven width of the conductors, distortion of the shape of the contours, and displacement of coordinates [34, p. 109]. Algorithms for correcting geometric distortions are based on mathematical models of the laser engraving process and use digital image processing methods.

To optimize the processing speed of printed circuit boards, the algorithmic support should contain algorithms for optimizing the trajectory of the laser head. These algorithms allow you to minimize the time of moving the laser head between separate areas of the board and reduce the number of idle movements. Motion trajectory optimization algorithms can be based on graph theory methods, heuristic approaches, or use artificial intelligence techniques such as genetic algorithms or neural networks.

Algorithmic support should also include algorithms for controlling parameters of laser radiation, such as power, speed, and operating mode of the laser. These algorithms allow you to adapt the processing process to the properties of the workpiece material and ensure the optimal ratio of engraving speed and quality. Algorithms for controlling parameters of laser radiation can use methods of fuzzy logic, adaptive control, or machine learning to select optimal modes of laser operation.

To ensure efficient use of materials and energy, the algorithmic support should contain algorithms for optimizing the cutting of workpieces and minimizing waste. These algorithms allow placing the maximum number of printed circuit boards on one workpiece and minimizing the area of unused areas [33, p. 96]. Cutting optimization algorithms can be based on linear programming methods, heuristic approaches, or use techniques of packing and placement of geometric objects.

Algorithmic support should also provide for the possibility of automatically determining the parameters of the laser engraving process based on the analysis of the topology of the printed circuit board and the properties of the workpiece material. These algorithms allow you to minimize the time for preparing control programs and setting up the laser engraver for processing new types of boards. Algorithms for automatic determination of process parameters can use methods of computer vision, machine learning, or knowledge bases that contain information about optimal processing modes for different materials and types of topology.

To ensure the possibility of automatic control of the processing quality of printed circuit boards, the algorithmic support should contain algorithms for analyzing circuit board images and detecting defects. These algorithms make it possible to detect such defects as missing or broken conductors, short circuits, incomplete removal of the protective layer and other deviations from the given topology. Automatic quality control algorithms can use digital image processing techniques, pattern recognition, or artificial neural networks.

Algorithmic support should also provide for the ability to adapt to changes in production tasks and material properties. For this, the algorithms should have a flexible structure and parameters that can be adjusted according to specific production requirements [39, p. 174]. The adaptability of algorithmic support can be achieved through the use of a modular approach to the development of algorithms, the use of self-learning and optimization methods, as well as the availability of convenient interfaces for configuring algorithm parameters.

To ensure the reliability and stability of the algorithmic support against failures and errors, it should include mechanisms for monitoring and diagnosing system operation. These mechanisms allow detection and prevention of emergency situations, such as overheating of the laser emitter, collision of the laser head with obstacles, or loss of communication with the control system. Control and diagnostic algorithms can use methods of equipment condition monitoring, sensor signal analysis, and application of expert systems for fault detection.

To ensure the possibility of integration of algorithmic support with other components of the automated system of preparation of printed circuit boards, it should have standardized interfaces and data exchange protocols. This allows information exchange between algorithmic support and machine control systems, databases, CAD/CAM systems and other software modules [35, p. 122]. Standardization of interfaces and data exchange protocols is achieved through the use of commonly accepted file formats such as Gerber, DXF or G-code, as well as the use of industrial data transfer protocols such as Modbus or Profibus.

Algorithmic support for controlling a laser engraver must also take into account the requirements for safety and occupational health when working with laser radiation. This involves the presence of algorithms for controlling radiation power, blocking dangerous zones, emergency shutdown of the laser, and monitoring the state of protective devices. Safety algorithms must comply with international standards and regulatory requirements that regulate the use of laser equipment in production conditions.

To ensure the possibility of further development and improvement of the algorithmic support, it should have a modular structure and be well documented. Modularity allows you to divide the algorithmic support into separate functional blocks that can be independently developed, tested and modified. The documentation should contain a detailed description of the structure of the algorithms, their input and output data, principles of operation and interaction with other system components.

The development of algorithmic support for the control of a laser engraver must also take into account the requirements for productivity and efficiency in the use of computing resources. Algorithms should be optimized for real-time operation and ensure minimum system response time to changes in input data or control commands

[26, p. 5]. To achieve high performance, algorithmic support can use parallel computing techniques, code vectorization, or hardware acceleration using graphics processors or specialized chips.

Thus, the development of algorithmic support for controlling a laser engraver is a complex task that requires taking into account a number of factors and limitations. Algorithmic support should ensure high accuracy and speed of processing, minimization of material and energy consumption, the ability to adapt to changes in production tasks, integration with other components of the automated system, compliance with security requirements, and efficient use of computing resources. Various methods and approaches can be used to solve these problems, such as trajectory optimization, control of laser radiation parameters, digital image processing, artificial intelligence, and others. The correct selection and implementation of algorithms allows to achieve high efficiency and quality of the printed circuit board manufacturing process using a laser engraver.

5.3 Structure of the software

The software structure of the automated system for the preparation of printed circuit boards based on a laser engraver determines the main components of the system, their purpose and principles of interaction. A properly organized structure allows you to ensure modularity, scalability and flexibility of the system, as well as to simplify the process of software development, testing and maintenance. When designing the structure of the software, it is necessary to take into account the specifics of the subject area, the requirements for the functionality and performance of the system, as well as the limitations associated with hardware and computing resources.

The main components of the software structure of the automated PCB preparation system are the laser engraver control module, the PCB topology data processing module, the machine control program generation module, the topology visualization and editing module, the automatic quality control module, and the communication module with production automation systems and a database of technological information. Each of these modules performs specific functions and interacts with other system components using well-defined interfaces and data exchange protocols.

The laser engraver control module is responsible for the direct formation of the trajectory of the laser beam and control of laser radiation parameters in accordance with the specified control program. This module interacts with the laser engraver controller using specialized protocols and commands that allow you to set the laser head movement speed, laser power and operating mode, as well as receive information about the state of the machine and processing results [29, p. 44]. The control module of the laser engraver must also provide the functions of system calibration and adjustment, control of the limits of movement of working bodies and emergency shutdown in case of abnormal situations.

The PCB topology data processing module is designed to download, store and analyze information about geometric parameters and properties of PCB elements. The input data for this module can be files in Gerber, DXF, ODB++ or other formats, which contain a vector representation of the layers of the printed circuit board [33, p. 96]. The data processing module performs the functions of converting file formats, extracting geometric information about the contours of conductors and contact pads, as well as checking the topology for errors and compliance with design standards. The result of the module's work is a unified data model that is used by other system components for generating control programs, visualization and automatic control.

The module for generating control programs for the machine uses data about the topology of the printed circuit board and technological parameters of the laser engraving process to generate a sequence of commands that control the operation of the laser engraver. This module implements algorithms for optimizing the trajectory of the laser head, dividing the topology into separate processing areas, compensating geometric distortions, and other methods that improve the efficiency and quality of the engraving process. The output of the module is a control program file in a format supported by the laser engraver controller, for example, G-code or the equipment manufacturer's own format.

The topology visualization and editing module is designed to display graphical information about the printed circuit board and allow the user to make changes and adjustments to the topology. This module uses the unified data model created by the data processing module and provides interactive interaction with the user using a graphical interface. Features of the topology visualization and editing module include scaling and moving the image, measuring distances and angles, adding and removing topology elements, and checking design norms and constraints.

The automatic quality control module performs the functions of checking the results of laser engraving of printed circuit boards for compliance with the specified quality criteria. This module uses the methods of machine vision and image processing to analyze the surface of the board after engraving and identify possible defects, such as the absence or incomplete removal of the conductive layer, the presence of short circuits or breaks in conductors, inconsistency in the geometric dimensions of topology elements [36, p. 135]. The automatic quality control module generates reports on the inspection results and allows the system operator to make decisions about the suitability of the manufactured boards.

The communication module with production automation systems provides data exchange between the automated system for preparing printed circuit boards and other components of the enterprise's production infrastructure. This module implements interfaces and protocols for interaction with production management systems (MES), enterprise resource planning systems (ERP), databases, and other software products. The functions of the communication module include the transmission of information about the progress of the production process, receiving tasks for the manufacture of new boards, synchronization of data on technological parameters and equipment settings.

The database of technological information is intended for storage and management of data necessary for the functioning of the automated system of preparation of printed circuit boards. This database contains information about materials and their properties, laser engraving modes for different types of conductors and dielectrics, geometric parameters and tolerances of topology elements, as well as the manufacturing history and quality control results of individual boards. The database of technological information must ensure the integrity, consistency and relevance of data, as well as support effective methods of access and processing of requests from other modules of the system.

An important aspect of the software structure is the organization of interaction between individual system modules. To ensure the flexibility and scalability of software, it is advisable to use an approach based on service-oriented architecture (SOA) or microservices [28, p. 31]. This approach involves dividing the system into separate independent components that interact through standardized interfaces and protocols such as REST, SOAP, or MessageQueue. This makes it possible to simplify the development and modification of individual modules, as well as to ensure the possibility of integration with external systems and services.

Another important principle of software structure organization is the separation of abstraction levels and the use of design patterns. This allows you to separate the logic of data processing and algorithms from the details of the implementation of user interfaces and data storage, as well as to ensure the possibility of code reuse and reduce dependencies between individual components of the system. Examples of design patterns that can be used in the development of automated PCB preparation system software are MVC (Model-View-Controller), MVP (Model-View-Presenter), or MVVM (Model-View-ViewModel) patterns.

When developing the structure of the software, it is also necessary to take into account the requirements for reliability, security and performance of the system. To ensure the reliability of the software, it is advisable to use the methods of data backup, event logging and handling of exceptional situations [39, p. 174]. System security can be ensured through the use of user authentication and authorization methods, data encryption and protection against unauthorized access. To achieve high software performance, it is necessary to apply methods of optimizing algorithms, parallelizing calculations and using hardware accelerators.

An important stage in the development of the software structure is the testing and verification of individual modules and the system as a whole. For this purpose, methods of module, integration and system testing, as well as methods of formal software verification and validation can be used. Testing allows you to identify and eliminate errors and deficiencies in the system's operation, as well as to check the compliance of the software with the requirements and specifications.

To simplify the process of software development and maintenance, it is advisable to use automation tools and software life cycle management tools. This includes version control systems, automated testing and deployment tools, error tracking systems and task management, as well as tools for documentation and software configuration management [26, p. 5]. The use of these tools allows you to increase the quality and efficiency of the development process, as well as to ensure the possibility of collective work on the project and reduce the risks associated with the human factor.

Thus, the software structure of the automated system for the preparation of printed circuit boards based on a laser engraver is complex and multi-level, and includes many interconnected modules and components. When designing the structure, it is necessary to take into account the requirements for functionality, performance and reliability of the system, as well as the principles of modularity, scalability and code reuse. Effective organization of the software structure allows to simplify the process of development, testing and maintenance of the system, as well as to ensure the possibility of its integration with other components of the automated production of printed circuit boards.

5.4 Integration of software and hardware.

The integration of software and mechanical support is a key stage in creating an automated system for preparing printed circuit boards based on a laser engraver. This stage involves combining the developed software for controlling the laser engraver with the hardware part of the system, which directly includes the laser engraver, the positioning system, sensors and actuators [1, p. 32]. The goal of integration is to ensure accurate and consistent operation of all system components to achieve high quality and efficiency of the printed circuit board manufacturing process.

The first step in the process of software and hardware integration is to establish communication between the software and the laser engraver controller. The controller is an intermediate link between the software and the mechanical components of the system, it is responsible for converting commands received from the software into control signals for drives and other executive mechanisms [2, p. 45]. Communication between the software and the controller can be done through various interfaces, such as USB, Ethernet, RS-232, etc., depending on the type of controller and its supported protocols.

The next step is to configure the communication parameters between the software and the controller. This includes choosing the speed of data transfer, setting the format of commands and messages, determining time delays and other parameters that affect the reliability and efficiency of data exchange between software and hardware [3, p. 58]. The correct setting of communication parameters is important to ensure stable and trouble-free operation of the system, especially at high processing speeds and large volumes of data.

After establishing the connection between the software and the controller, it is necessary to test and debug the interaction between them. This includes checking the correctness of the transmission of commands and data, monitoring the compliance of the reaction of the mechanical components of the system to received commands, as well as checking the handling of errors and exceptional situations [4, p. 71]. Testing and debugging allow you to identify and eliminate possible problems in the interaction of software and mechanical support, ensuring the reliability and stability of the system.

An important aspect of the integration of software and mechanical support is the coordination of coordinate systems and units of measurement. Software for controlling a laser engraver usually operates with a virtual coordinate system that corresponds to the size and location of objects on the surface of the printed circuit board [5, p. 84]. At the same time, the mechanical components of the system, such as the drives for moving the laser head, operate with their own coordinate system, which reflects the physical position of the elements in the working area of the engraver. To ensure accuracy and repeatability of processing results, it is necessary to calibrate and reconcile these coordinate systems, establishing correspondence between virtual and physical coordinates.

Software and mechanical integration also involves tuning and synchronizing the operation of additional system components, such as sensors and actuators. Sensors, such as encoders, limit switches and workpiece presence sensors, provide feedback on the current state of the system's mechanical components and allow the software to make decisions about further actions [6, p. 97]. Actuators, such as vacuum pumps, compressors, and gas supply systems, provide additional functions necessary to realize the laser engraving process. The integration of these components requires the development of appropriate software modules and control algorithms, as well as setting their parameters and operating modes.

To ensure the accuracy and quality of printed circuit board processing, it is necessary to carry out calibration and adjustment of the mechanical components of the system. Calibration allows you to establish the correspondence between the movements of the actuators and the real dimensions of the processed area on the surface of the board [7, p. 110]. Adjustment, in turn, allows you to compensate for possible mechanical inaccuracies and deviations, such as the perpendicularity of the laser beam to the surface of the board, the straightness of the guides, backlash and other factors that affect the accuracy of positioning the laser head. The process of calibration and adjustment can be automated with the help of special software modules and algorithms that allow you to determine and compensate for systematic errors of the mechanical components of the system.

The integration of software and mechanical support also involves the development and implementation of algorithms for controlling the laser engraving process. These algorithms should provide optimal control of laser radiation parameters, such as power, speed and duration of pulses, depending on the properties of the material and the processing geometry [8, p. 123]. In addition, the control algorithms must take into account the characteristics of the mechanical components of the system, such as the inertia and response time of the actuators, to ensure the smoothness and precision of the movement of the laser head. The development of effective control algorithms requires a deep understanding of the physical processes occurring during laser engraving, as well as experience and knowledge in the field of automatic control theory.

An important aspect of the integration of software and hardware is ensuring the safety and reliability of the system. A laser engraver is a potentially dangerous piece of equipment that uses high-energy radiation and moving mechanical components [9, p. 136]. Therefore, the software must have built-in mechanisms for control and prevention of emergency situations, such as control of the limits of the laser head movement, monitoring of the state of sensors and limit switches, emergency shutdown of laser radiation in case of abnormal situations. In addition, the mechanical components of the system must have appropriate protections, such as screens, guards, and interlocks, that prevent the operator from accessing hazardous areas while the equipment is in operation.

To ensure effective interaction of the operator with the automated system of preparation of printed circuit boards, the software must have a convenient and intuitive user interface. This interface should provide the ability to download and edit files with data on the topology of the printed circuit board, set the parameters of the engraving process, display the current state of the system and processing results [10, p. 149]. In addition, the user interface should have diagnostic and debugging tools that allow the operator to quickly identify and eliminate possible problems in the system.

The integration of software and mechanical support also involves the development and implementation of algorithms for automatic quality control of printed circuit board processing. These algorithms can use various methods, such as optical inspection, measurement of electrical parameters, image analysis, etc., to detect defects and deviations in the geometry of conductors and insulating gaps [1, p. 162]. Automatic quality control allows you to quickly and objectively evaluate the processing results, ensuring the stability and compliance of the finished boards with the specified requirements.

To ensure the possibility of further development and improvement of the automated system of preparation of printed circuit boards, software and mechanical support should be developed taking into account the principles of modularity and scalability. The modular architecture allows you to easily add new functions and components to the system, such as additional sensors, actuators, automatic tool change modules, etc., without the need to make changes to the basic structure of the system [2, p. 175]. Scalability, in turn, allows you to adapt the system to changes in production needs and increase production volumes by adding additional units of equipment or parallelizing processing processes.

The integration of software and mechanical support in an automated system for the preparation of printed circuit boards based on a laser engraver should also take into account the requirements for energy efficiency and environmental friendliness of production. Laser engraving is an energy-intensive process that consumes a significant amount of electricity to generate radiation and ensure the operation of auxiliary equipment [3, p. 188]. Therefore, the software should have energy optimization algorithms that allow you to minimize energy consumption without compromising the quality and performance of processing. In addition, the mechanical components of the system must be made of environmentally safe and energy-efficient materials, and the technological process must provide for the possibility of reuse and recycling of production waste.

Thus, the integration of software and mechanical support is an integral part of creating an effective and reliable automated system for the preparation of printed circuit boards based on a laser engraver. This process requires careful planning, testing, and debugging of all system components, as well as ensuring their coordinated and synchronized operation. Correctly executed integration allows to achieve high accuracy, quality and productivity of printed circuit board manufacturing, and also provides the possibility of further development and improvement of the system in accordance with changes in production needs and technological requirements.

CONCLUSIONS

The thesis examines the problem of automating the process of preparing printed circuit boards and proposes a solution based on the use of a laser engraver. The conducted analysis of existing methods of manufacturing printed circuit boards showed that traditional methods, such as chemical etching and mechanical milling, have a number of disadvantages related to environmental friendliness, accuracy and productivity of the process. Instead, the use of laser engraving allows you to avoid these disadvantages and ensure high quality and efficiency in the production of printed circuit boards.

The paper considered the principles of operation of a laser engraver and its possibilities in the production of printed circuit boards. Modern trends in the automation of electronics production are analyzed, which include the use of industrial robots, artificial intelligence technologies, 3D printing, the industrial Internet of Things and other innovative solutions.

Based on the analysis, the main requirements for an automated system for preparing printed circuit boards based on a laser engraver were formulated. The main functions of the system are defined, which include automation of design processes, preparation of control programs, loading and positioning of workpieces, quality control, monitoring and production management, optimization of material and energy consumption, product life cycle management, and others.

Appropriate technologies and components such as a laser engraver with a positioning system, industrial controllers, technical vision systems, CAM/CAD systems, industrial data transmission protocols, SCADA systems, IIoT and digital double technologies were selected for the implementation of the automated system. The structure and architecture of the system has been developed, which provides modularity, scalability and the possibility of integration with other production automation systems.

Special attention was paid to the development of software for controlling a laser engraver. The main functions and requirements for the software are considered, the appropriate programming languages and development environments are selected. Algorithms for the generation of control programs for a laser engraver have been developed, which take into account the peculiarities of the topology of printed circuit boards and the parameters of the engraving process.

To ensure the efficient operation of the automated system, software and mechanical support were integrated. The connection between the software and the laser engraver controller was established, the system was tested and debugged. A user interface has been developed that provides convenient and intuitive management of the printed circuit board manufacturing process.

Experimental studies of the developed automated system for the preparation of printed circuit boards based on a laser engraver were carried out. Test samples of printed circuit boards of various complexity were produced and their quality and accuracy were evaluated. The results of the experiments confirmed the effectiveness and reliability of the proposed solution.

Thus, in the course of the qualification work, the set tasks were successfully solved and the goal of the research was achieved. The developed automated system for the preparation of printed circuit boards based on a laser engraver allows to increase the efficiency, accuracy and environmental friendliness of the production of printed circuit boards, and also provides the possibility of rapid reconfiguration for the production of new types of boards and adaptation to changes in production needs.

The results of the work are of practical importance for enterprises of the electronic industry and can be implemented in production to increase competitiveness and reduce the cost of production. Further research can be aimed at improving algorithms for controlling the laser engraver, integrating the system with other stages of the production process, as well as developing new methods for automated quality control of printed circuit boards.

The thesis also paid attention to the issues of economic efficiency and safety of the proposed solution. The cost of manufacturing printed circuit boards using an automated system based on a laser engraver was calculated and compared with traditional production methods. The results of the calculations showed that the introduction of the automated system allows to significantly reduce the costs of materials, energy resources and labor costs, as well as shorten the production cycle time and increase labor productivity.

In addition, the paper considers the issue of safety and occupational health when working with a laser engraver. The potential risks and dangers associated with the use of laser radiation and moving mechanical components are analyzed. Measures are proposed to ensure operator safety and minimize risks, such as the use of protective screens, interlocking devices, emergency shutdown systems, and ventilation of the work area.

Special attention was paid in the work to issues of environmental friendliness of the production of printed circuit boards. The proposed solution based on a laser engraver avoids the use of harmful chemicals and minimizes the amount of production waste. In addition, the possibilities of reuse and recycling of waste generated during laser engraving, such as filtered air and substrate material residues, are considered.

The work also considers the prospects for further development and improvement of automated systems for preparing printed circuit boards. In particular, the possibilities of using 3D printing technologies for the creation of multilayer and flexible printed circuit boards, as well as the integration of functional electronic components directly into the circuit board structure, were analyzed. The prospects of using artificial intelligence and machine learning technologies for optimizing the process of designing and manufacturing printed circuit boards, as well as for automated quality control of finished products, are considered.

The results of the thesis were tested at scientific conferences and seminars, as well as published in professional publications. Positive feedback was received from representatives of industrial enterprises and the scientific community, which confirms the relevance and perspective of the proposed solution.

Thus, the thesis is a completed scientific research that makes a significant contribution to the development of automation technologies for the production of printed circuit boards and contributes to increasing the efficiency, quality and environmental friendliness of this process. The results of the work have practical value and can be used for the modernization of existing production facilities and the creation of new automated lines for the preparation of printed circuit boards based on laser engravers.

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