Automated system design for experimental research of the technological process parameters of spacecraft waveguide paths induction soldering

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Abstract. The paper describes the developed software model functional for conducting experimental research of spacecraft waveguide paths induction soldering. A diagram of use cases allowing more detailed formalization of the functional requirements for the developed system from the user's point of view has been built. The architecture of the future system is presented. A way to improve the quality of soldering in the form of solution of the experiment automation and planning problem, which has not been previously considered, is proposed. The results of the work will allow developing a system that will carry out process modeling without resorting to real tests, with data processing and analysis.

1. Introduction
Waveguide paths are an important detail of satellite television and radio communications. They ensure functioning of both a spacecraft itself and its on-board equipment. The waveguide path of a spacecraft is a thin-walled tube of rectangular cross section. The main method of producing waveguide paths is soldering by induction heating. This technology allows producing parts that exactly meet the required characteristics [1]. However, this process has a number of features that greatly complicate it and put forward additional requirements for the accuracy of positioning the manufactured product, the shape of the inductor, and the parameters of the induction brazing generator. On this basis the problem of automating the study of the dependencies of various process parameters becomes relevant.

Modern instrument-making industry provides access to an extensive set of measuring devices, complexes and installations for solving the problems of automating experimental research. Such equipment is mainly expensive and often does not provide for the satisfaction of all research needs. In addition, the narrow focus of the finished devices significantly limits the researcher’s opportunities in planning the experiment and the closeness of these devices does not allow them to be finalized until the desired functionality appears. It is also worth noting that despite the fact that modern measuring systems come with ready-made software, this software often does not allow solving the problems that the researcher faces in the form the researcher wants.
Most experimental studies require an individual approach to their automation with the development of specialized software. Therefore, the use of universal computer-measuring systems is inevitable to solve such problems.

A modern automated technological experiment should provide not only reading the sensors, but also controlling the experiment process, transferring the data in a digital form to the control computer, data analysis, processing and visual interpretation in a form convenient for the experimenter. In addition, the hardware and software of the instrumental support of the experiment should have the necessary reliability. Therefore, in order to meet all the above requirements, the researcher involved in the development and design of automation systems for a technological experiment requires not only knowledge in the subject field, but also knowledge of computer technology, electronics, and programming [2]. Besides, the installation being developed should solve such problems as simplifying the procedure of experiment conducting and reducing the time for experiment preparing, the time for conducting the experiment itself, and the time for data processing.

Thus, the goal of this project is to develop an automated system of experimental research of technological processes, which allows conducting technological experiments and full scale tests, obtaining experimental data, and also analyzing and evaluating them.

2. Literature review
The basic method for planning an experiment is orthogonal plans of the first and second order. Let us consider the software that makes such plans [3]. This software, implemented in the form of macros in the language of Visual Basic for Applications running in the Microsoft Excel application environment and interacting with the Microsoft Access database, allows downloading from the outside, storing and processing the results of experimental research. The application considered this way helps to simplify experiments. However, the considered software contains a number of disadvantages, such as interaction only with the Access DBMS and the impossibility of automatically downloading data from any other sources. Also, it lacks the ability to make plans of other types.

The work [4] presents a software product capable of processing data from factorial experiments, including fractional factorial experiments. The program can perform assessment of the model adequacy and display all the estimates calculated in the process. The disadvantages of the software product include undeveloped data download tools, including the inability to automate this process. Also, the product under consideration imposes restrictions on the number of factors and experiences of steepest ascent on the response surface associated with the organization of the program output. Although these restrictions are not fundamental, they greatly narrow the scope of the program.

The system described in [5] is a hardware-software complex that provides the ability to automate experimental research of one specific type of objects, namely internal combustion engines. This system has a functional for the direct collection and storage of external data in an automatic mode. Despite the narrow scope of this software-hardware complex, it can serve as an example of more complete automation of technological processes experimental research than the software products considered before it.

On the basis of the products and systems reviewed it can be concluded that the problems of experiment automation in the general case have not been solved. General solutions are not functional enough, and solutions with a wider functional are tied to specific research objects. In this regard, the problem of developing such a system for induction soldering of waveguides can be considered urgent.

3. Statement of the problem
The system under development should include the functional of the previously developed induction soldering process system [6] through integration with existing modules, and also have a new module for the possibility of conducting experimental research.

The existing system collects pyrometry data by interacting with pyrometers through COM interfaces. It is possible to configure such parameters of the pyrometer as the emission factor. This system also allows automated control of the soldering process using a proportional controller. The system lacks the...
functional for processing experimental data and constructing mathematical models. Taking into account a small set of data collected, it can be concluded that the system under consideration does not satisfy the goals set in the introduction.

Let us proceed to considering the system of experimental research automation [7]. This system allows conducting experiments with induction soldering and saving the information accumulated as a result of them. In particular, the system provides the opportunity to make changes to the input parameters of the process directly during its implementation. The main measured and controlled parameters for this system are the position of the waveguide preform and the process temperature. The system lacks automation of making plans of experiments and processing results, and in general the system only simplifies the direct conduct of the experiment.

The system provides for two users: an operator and a technologist. An operator can view the results of experiments recorded in the database. A technologist performs the experiment, processes the data, and controls the process.

![Diagram of use cases](image)

**Figure 1.** Diagram of use cases.

Conducting any technological experiment consists of the following steps:

- development of experimental techniques;
- data collection, recording on media, primary data processing;
- secondary data processing, including mathematical processing of the obtained results and error estimation;
- analysis of the results.
On the basis of this, the software system under development should have the following functionalities:

- computational process management (accounting, control, analysis of the calculation progress);
- collection of information from measuring tools;
- registration and storage of measurement information in the database;
- manual input / loading of data from a file;
- visualization of measurement information in the form of tables, diagrams, reports;
- control of equipment and process parameters;
- primary processing of measurement information, screening of abnormal measurements, assessment of measurement errors;
- planning a measurement experiment;
- statistical processing of experimental data;
- calculation of mathematical models;
- study of models, development of object control algorithms in a real process.

A diagram of the use cases of the developed software system is presented in figure 1. Figure 2 shows the architecture of the developed system.

![Figure 2. Architecture of the developed system.](image-url)

4. Description of the developed system functional

The general scheme of controlling the computational process is as follows. Sensors and actuators are directly connected to a specialized device for data collection and control. The analog-digital and discrete-digital converters built into the data acquisition board digitize the input signals. The received measurement information in real time serves to visualize and control the process using the appropriate interface, and it is also archived for further processing. The calculated data necessary to maintain normal process parameters are transmitted to the actuators using digital-analog and digital-discrete converters.

Thus, using a set of automatic devices and software the operator receives the information about the state of the technological object from measuring devices and influences the object in order to achieve the normal functioning of the technological process.

Collection and processing of measurement information is used in natural and model studies to determine conditions and analyze the process. One of the main tasks in processing experimental research data is the construction of a technological object mathematical model and its study [8]. In the general
case, most studies using experiments are carried out with the aim of establishing a statistically significant relationship between dependent and independent variables, predicting (restoring unknown values) of the studied resulting features (dependent variables), and also identifying causal relationships between independent and dependent variables.

The study of objects of technological processes includes the following stages of processing experimental data:

- substantive analysis of the experiment;
- devising the plan of the experiment (determination of the independent variables values, selection of test signals, estimation of the observation volume). Preliminary selection of methods and algorithms for statistical processing of experimental data;
- conducting experimental research, collecting experimental data, recording it and entering into the program;
- preliminary statistical data processing, intended primarily to verify the fulfillment of the premises underlying the selected statistical method for constructing a stochastic model of the object under study, and if necessary, to correct the a priori model and select another processing algorithm;
- making a detailed plan for further statistical analysis of experimental data;
- statistical processing of experimental data (secondary, complete, final processing), aimed at building a model of the object under study, and statistical analysis of its quality. Using the built model;
- formal-logical and informative interpretation of the results of experiments, making decision on the continuation or completion of the experiment, summarizing the results of the study.

The measurement information is processed and analyzed after loading it with the help of the developed experiment. The process of researching technological process objects can be conditionally divided into the following stages: preliminary data processing, planning and execution of the experiment itself, processing of experimental data.

The ultimate goal of preliminary processing of experimental data is to put forward hypotheses about the class and structure of mathematical models of the studied technological processes, and to determine the composition and volume of measurements. During the initial data processing the following list of problems is solved: conversion to a nominal or ordinal scale; exclusion of sharply distinguished observations (emissions); restoration of missed observations; checking the statistical independence of the observations sequence; checking compliance with the selected distribution law; putting forward and testing the hypothesis of functional relationships between the studied factors. The prepared data is then used in the experiment.

At present, methods of experiment planning are widely used in experimental research, which in many cases allow obtaining adequate mathematical models of studied objects with a minimum number of experiments [9].

At each step of planning an experiment a small series of subexperiments is performed. In each of these subexperiments all factors (variables) vary according to certain algorithms. Mathematical processing of the experimental results allows developing strategies of conducting the next series of subexperiments to achieve the goal.

Methods based on two main components of the apparatus of mathematical statistics, namely, on the theory of statistical estimation of unknown parameters used to describe the experimental model and the theory of testing statistical hypotheses about the parameters or nature of the analyzed model, are used in solving the problems of processing experimental data. For these purposes, a user will be given an opportunity to use the following experimental data processing methods.

**Correlation analysis.** The purpose of correlation analysis is to determine the presence or absence of a relationship (usually linear) between two or more random variables. These random variables are input independent variables, as well as the resulting (dependent variable). Using correlation analysis allows
selecting all the factors in the model that have the most significant effect on the resulting variable. The selected values are used for further analysis, in particular when performing a regression analysis. Correlation analysis allows detecting previously unknown cause-effect relationships between variables. It should be born in mind that the presence of correlation between variables is a necessary, but not a sufficient condition for the presence of causal relationships [10].

Analysis of variance. Analysis of variance is intended to process experimental data depending on qualitative factors and to assess the significance of the influence of these factors on the observation results. Its essence consists in decomposing the resulting variable variance into independent components, each of which characterizes the influence of a particular factor on this variable. A comparison of these components allows assessing the significance of the influence of factors [11].

Regression analysis. Regression analysis methods make it possible to establish the structure and parameters of the model linking the quantitative resulting variable and factor ones, and to assess the degree of its consistency with experimental data. This type of statistical analysis is the main one in processing experimental data [12].

Factor analysis. Its essence lies in the fact that the "external" factors used in the model and highly interconnected should be replaced by fewer "internal" factors, which are difficult or impossible to measure, but which determine the behavior of "external" factors and thereby the behavior of the resulting variable. Factor analysis makes it possible to put forward hypotheses about the structure of the relationship of variables without specifying this structure in advance and without having any preliminary information about it. This structure is determined by observation. The resulting hypotheses may be tested in further experiments. The object of the factor analysis is to find a simple structure which would sufficiently accurately reflect and reproduce real existing dependences [13].

5. Conclusion
During the research the existing solutions in the field of collecting and processing experimental data were considered and the functional of the future software solution was developed. The functional allows constructing various models of the process of spacecraft waveguide paths induction soldering and applying them in real conditions on an automated system. The integration with the existing automated system is described. An application of the experiment planning method is proposed. The process of data processing and analysis is considered; various methods for processing experimental data in the developed system are presented.

In the future an automated control system for the process of spacecraft waveguide paths induction soldering will be developed on the basis of the work done and the functional described. The system will reduce production costs and improve the quality of manufactured products.

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