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METHOD FOR TESTING THE SINGULAR AND UNIQUE TECHNICAL DEVICES

Key words

Prototype testing, decomposition, prototyping, verification.

Abstract

The achieved level of design methods and manufacturing of technical equipment enables rapid production of a fully functional prototype or standalone device. The required efficiency of prototyping methodology introduces the need for testing prototypes with use of knowledge accumulated in a database that contains descriptions of historical problems of construction, testing, commissioning, and implementation.

The paper presents the methodology of testing the unique and singular technical solutions for supporting the advanced prototyping of new innovative products that were developed at the Institute for Sustainable Technologies.

The aim of this work was to develop a solution, in the form of a system of testing for prototypes, enabling the control of the process of testing with a method based on the resources of accumulated knowledge concerning the design, commissioning, and implementation of high-tech equipment, performed individually or in a series. The use of testing methodology increases the guarantee

of the development of prototype machines and devices that are characterised with the better quality and reliability as compared to solutions based only on the knowledge acquired and experience of the implementation team members. Pilot operated testing methodology has been applied to several prototype devices designed and constructed at the Institute for Sustainable Technologies.

Introduction

Prototyping of technical equipment is an activity that requires a methodical approach to ensure the achievement of planned targets in the time provided for the project while maintaining technical, qualitative, financial, and organizational rigor. This process is particularly difficult for the design of equipment that, in the current state-of-the-art, does not have equivalents, or earlier development versions. The issue becomes even more complex if the object representing the result of design is a unique solution, characterised by a high degree of innovation, which exists only in the form of a single prototype [1].

The achieved level of production and design methods for technical devices allows rapid production of a fully functional prototype of a singular device. That does not mean automatic development of a product with the required parameters of durability, functionality, and meeting customer expectations. A significant difficulty in prototyping of solutions is to guarantee the high quality of the outcome of the work. An increase in the efficiency of prototyping processes requires the use of a testing method for prototypes using resources such as knowledge accumulated in a database of historical problems of construction, testing, commissioning, and implementation.

1. Evolution of testing methods for prototype devices

The history of prototype testing is closely related to the history of inventions and the development of science and technology. Prehistoric, ancient, and antique machines built by man have always been prototypes. It was related to the limited access to knowledge resources and primitive methods of production that prevented accurate reproduction and production in a reproducible manner [2]. The first machines were invented and built for a specific application, in order to achieve a utilitarian aim, not considering the possibility of serial reproduction of practical solutions.

With the development of civilization, thanks to improvements in manufacturing technology, prototyping ceased to be associated with each new copy of the piece of equipment. The development of modern production techniques, the industrial revolution, and change in the organization of the manufacturing process have enabled the production of machine parts and finished devices in a reproducible manner that ensures the functional parameters of the solution.

Currently, the construction of machinery and equipment, as a result of a centuries-long process of cognitive and technological evolution, has reached a new quality. That quality depends on effective design, manufacturing, and implementation of unique prototypes in a commercially reasonable manner, with the highest requirements previously formulated only in mass production.

From individual solutions, built in past centuries, which uniqueness resulted from imperfect methods of production and reduced demand, through the industrial revolution of the nineteenth century, and the serial and mass production launched at the beginning of the twentieth century, thanks to technological progress achieved at the beginning of the XXI century, gave the possibility of building a unique, commercial prototypes, developed individually and customised. This is a momentous change in civilization, because the first machines were the prototypes for technological and social reasons, and present prototypes of unique machines are intentionally individualised, thanks to achieved technical capabilities. Modern prototype can be a fully functional product effectively meeting individual user's needs, being developed and produced in a unit scale.

2. General aims of the method

The basic premise for the development of a unique testing methodology for prototype devices is the lack of systemic measures aimed at gathering practical knowledge empirically gained in the process of prototyping and project management for the reuse of historical information in future operations, new initiatives in design, manufacturing, and implementation of innovative technical solutions, implemented in single copies or in a short series [3]. Most often, the use of information obtained based on the research is limited to use only for the current assessment of the test object at different stages of the implementation task.

Systematic intellectual capital that enables the processing of data is one of the main components used in the space of synergistic interactions taking place in the design process. Effective use of archival information resources contributes to the reduction of the risk in new projects and ensures effective risk management. Above all, however, it is a guarantee of the creation of prototype machines and devices that are characterized by better quality and reliability as compared to solutions based only on the knowledge acquired and experience of the implementation team members.

Management of testing of prototypes obliges one to acquire new knowledge and systematic storage of information in order to obtain the increasing efficiency of product implementation in less time and with the involvement of small financial outlay. Modern technical and economic factors have contributed to creating the need to build a database of findings and conclusions, accumulated at the end of each project, related to the implementation of unique and innovative technical equipment.

3. The organizational and technical conditions

The complexity of the machinery, equipment, and economic considerations lead to the conclusion that the process of testing the prototypes should focus only on selected issues, crucial for the correct operation and safety of operation. Exploration of all options, conditions, dependencies, and the configuration of cases at the stage of prototype testing involves spending too much time, financial and human resources, and equipment, in relation to the budget, which is not acceptable from the point of view of economics of the project. In this respect, the study of the prototypes of machines and equipment manufactured individually are in a particularly disadvantageous relationship to research of equipment manufactured in a series. Testing prototype devices individually made affect expenses the final price of the solution far more than in the case of mass production. In the extreme case of a single prototype, testing may be the dominant financial component of the developed unique solution, while, for mass-produced products, prototype testing costs can be negligible, in the settlement of all items offered to customers.

In the case of prototypes manufactured individually, it is required to reduce the complexity of the system under testing and the selection of the analysed signals, which are performed by omitting systems whose reliability is known or guaranteed by the supplier. This entails the risk of missing some of the dangers and can cause the formulation of an incorrect diagnosis and misevaluation of a prototype. These conditions mean that the risk is one of the important parameters of the process of the managing of testing of prototypes, particularly devices manufactured individually.

4. Characteristics of the testing system for prototypes

Prototype tests are used at all stages of life solutions, starting with design assumptions, then operation, and ending with recycling and disposal. Acquired and processed information from studies provide substantial support for current and future activities and organizational decision-making. Archiving research results is an activity that supports the creation of new knowledge about prototype solutions, stored in a common database accessible for designers. Replenishment of information in expert systems allows the use of previous experience in the design of new products.

In the assessment system for prototypes, there are two feedback loops (Fig. 1). The first is called “Small” and provides for the operation of the cycle of the product development. The second is called “|Large” and ensures the development of the research system.

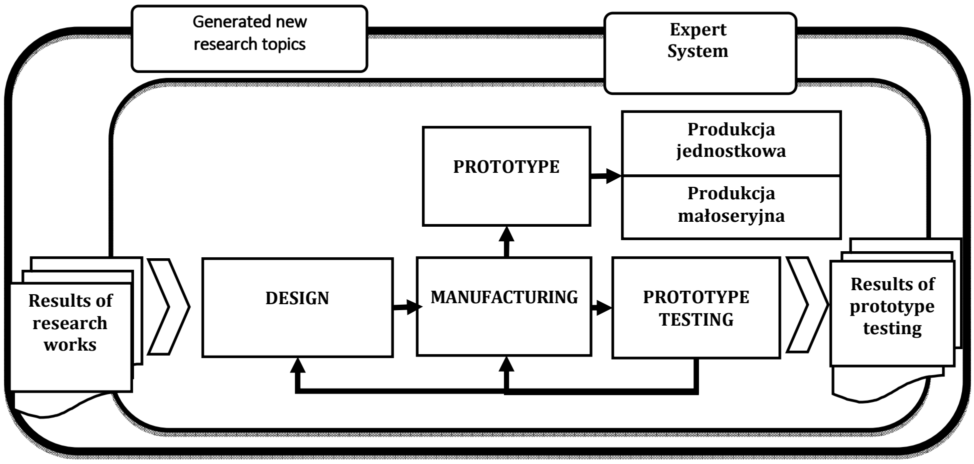

Fig. 1. Small and large feedback loops in the prototype testing system

The small feedback loop integrates design activities in the field of manufacturing design and testing prototypes. The prototype test results represent feedback that supplies the base of the expert system and is also a material used by a team of designers working on a new product. The collection of information, which is recorded in the database and processed in the context of the work of the expert system as a result of prototype tests, is a valuable source of information on similar solutions for structural and research problems. It is important to systematically supply data for all design changes and corrective actions taken, both effective and ineffective. As part of a small loop, the expert system is supplied with information on methods of testing devices, their effectiveness, and problems in specific applications for the examination of prototype devices. The large feedback loop integrates activities in the area between the research work and their results and the results of the testing of prototypes. In this case, the information contained in the expert system supports the generation of new research topics. Problems identified at the stage of the testing of prototypes or their preparation may be outstanding issues, which are structured and prepared as a subject for further research and development.

The concept of the methodology is consistent with the methods of the testing of equipment, using simulation techniques, analysis and experimental verification conducted in the laboratory, in simulated real-world conditions, test site conditions, and under real operating conditions. The use of databases to collect the results of observations refers to the solutions used in operational research systems, operating based on the collection of observations of reliability [4]. In [5], concerning the research methodology of the exploitation of the mechanical objects presented, are the characteristics of several programs dedicated to the collection of data on the intensity of damage to various types of devices, launched in the past few decades in aerospace, electronics, electromechanics, power plants [6], and the oil industry [7].

The methodology of testing prototypes introduced the ability to use external sources of information on the intensity and causes of damage, when the data exists and is available. Particularly important are the data obtained from operational observations and used for managing the operation, stored in data banks [8, 9].

5. The assumptions for methodology

The methodology focused on the use of previously collected results in the management of testing prototypes and designing new equipment is a basis for systemic data acquisition from the process of prototyping and computer processing, integrated in the design, manufacture, verification and operation process. The methodology supports the process of managing tests of prototypes with respect to the activities relating to the collection, storage, and processing of data and the analysis of cause and effect, in order to re-use the data in the planning and implementation of research.

Underlying assumptions for prototype testing methodology are the following essential statements:

- In each prototype there is some unavoidable uncertainty level about the functionality, durability, and reliability associated with the strategy of the testing process.
- Prototype testing is always carried out in a limited extent.
- The quality of the equipment must satisfy the customer, but it should not exceed defined expectations.
- Examination is associated with the entire period of the development of the device.
- Prototype tests are a source of information to be used in the process of the prototyping of next-generation solutions and the development of other machinery and equipment.

The process of testing and verification of unique prototype devices is understood as an ordered set of tasks, operations, and procedures performed on specific test stands by assigned staff, using the necessary control-measuring equipment in the necessary time period.

In particular, the prototype test methodology developed uses the following assumptions [10]:

- Prototype methodology applies to technical objects made in single units, individually or in a short series, and processes are not included.
- Technical object prototype is built of systems, components, parts, and computer procedures that can be extracted and which can be identified and assigned their impact on the quality of the whole solution.

- The development of a test plan is an iterative process that requires expert knowledge.
- There are known limitations of time and money associated with the process of the research and testing of a prototype.
- Each element/component/system/procedure can be tested (if an item is a part of a component assembly and cannot be tested separately, it is subjected to tests of the containing element).
- There are no operating characteristics of all prototype solutions, in particular, there is at least one of the following options:
  - There is no information about which elements are the most often damaged.
  - There is no information about what are the causes of the damage.
  - There is no information on the potential damage impact on the functioning of the whole prototype solution.
- It is possible to acquire the knowledge of experts (users, designers, builders, prototype contractors).
- Testing methods are known for the testing and verifying the proper operation of the prototype solutions, using the available control-measurement apparatus, which can be used in the laboratory or test bench.
- The methodology includes support for the identification procedures based on the analysis of cause-and-effect relationships and tools to document them.
- The methodology requires the evolutionary collection of the expert knowledge and failure data on elements, components, and modules and their frequency and data on the test methods and test apparatus and standard requirements.
- The methodology should allow the determination of the empirical relationship between quality and technical parameters using functional analysis, experience, analysis of the complaints, the cost of repairs, etc.
- The identification of the meaning of parameters of the technical components, assemblies, modules, and procedures, is essential for the forthcoming methodology.
- The methodology takes into account the relation (correlation) between the technical parameters.
- Faults (defects) of prototype, particularly accurately analysed, include functions that the prototype is to execute, reliability during operation, ease of use by the user, and ease of repair in case of damage.
- The methodology includes procedures to support the selection of the working group (number and type of experts), the definition of the extent and timing of research, functional decomposition, data collection, and qualitative and quantitative analysis of defects.

- The methodology applies stages of the construction of assumptions, design, construction, commissioning, testing, and verification of post-implementation operation.
- Only new, original solutions that are the result of research and development are subjected to tests.
- Excluded from the study are commercial components and sub-assemblies that have been verified with positive results from previous projects, if the technical requirements and functions are applicable and unchanged.

Because of the focus on the prototypes of technical objects, the methodology should at least include a set of qualitative and quantitative parameters describing the following:

- The physical and chemical properties of the prototype solutions, e.g. dimensions, chemical composition, and physicochemical properties;
- Economic parameters, e.g. manufacturing costs, research costs, projected operating costs, depreciation period, etc.;
- Operational properties, e.g. safety, durability, reliability;
- Ergonomic properties;
- Aesthetic properties;
- Environmental parameters and characteristics, particularly in the context of sustainable development of the economy;
- The cause-and-effect (quantitative and qualitative) relationships between the used components, sub-assemblies or modules and their failures and defects and their influence on the failure to obtain the assumed parameters and technical characteristics of prototype solutions;
- Quality (functional) requirements of the recipient of a prototype;
- The relationship between customer requirements and technical parameters; and,
- The types of testing and verification research, including any destructive testing necessary.

The aims of the application of the methodology are the following:

- The improvement of the quality and reliability of the devices manufactured individually and in short series;
- The identification of hazards and their measurement and evaluation;
- The identification of processes and functions occurring in the test device;
- The identification of the structure of the research object;
- The identification of the weaknesses and knowledge of the advantages of the prototype solution;
- The identification of areas requiring corrective action;
- The prediction of corrective actions;
- Shortening of the time and reduction of the cost of prototype tests, taking into account the technical, financial, organizational, and time limitations;

- The collection of information resources that can be used in the structure of the knowledge base;
- The development of simulation models of the device, especially under conditions of start-up or in an emergency; and,
- The development of new or existing measurement techniques, in particular, for the study of unique prototype solutions.

The utilitarian goal is the application of the methodology in the form of a computer system for testing prototypes that enables the testing of process control based on the resources of accumulated knowledge concerning the design, commissioning, and implementation of high-tech equipment, manufactured individually or in short series.

6. Characteristics of the methodology

The methodology requires the selection of the expert group responsible for the testing of prototype. This group includes system analysts, metrologists, diagnosticians, specialists in the field of systems engineering, experts with knowledge of the elements, components, and modules used for the construction of a prototype (Fig. 2). This group should be complemented with persons performing development work involving the testing of the operation of the prototype and verification of whether it has the expected functionality.

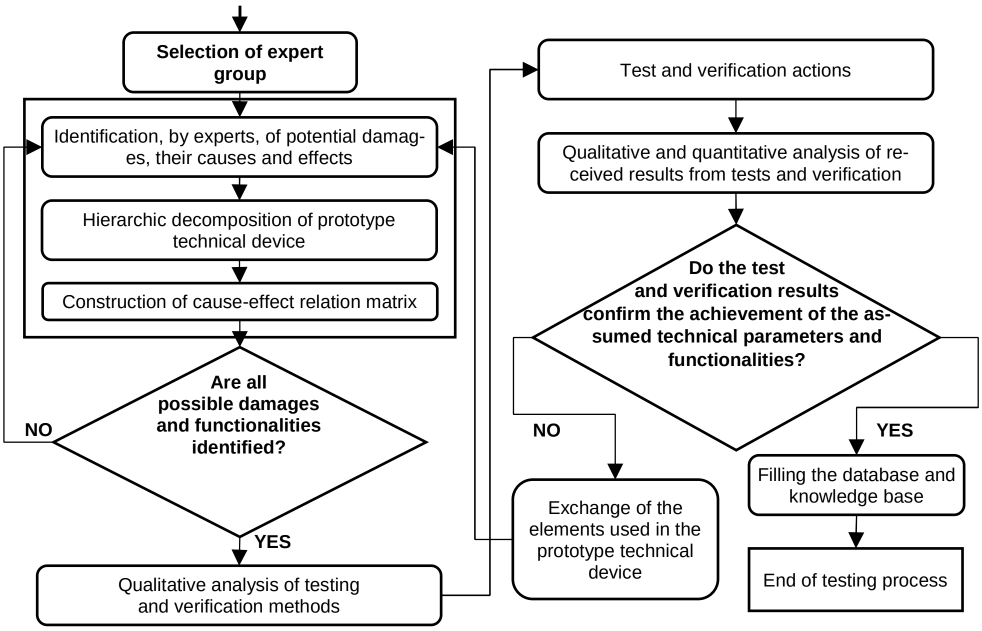

Fig. 2. Diagram of prototype testing methodology

System analysts in cooperation with the developers carry out the structural decomposition of the prototype solutions to elements, components, and modules [11]. The decomposition operation is completed with procedures to identify the physical, economic, ecological, and aesthetic properties of prototype. Before the examination, the specific operational objectives are formulated and matrix of technical parameters of the prototype is defined.

In order to verify the accuracy of the designation of a set of technical parameters, the use of kinship diagrams is proposed. The aim of their application is the organisation and logical presentation of relationships, including the correlation between technical parameters and quality features [12]. After the verification of the operation of a set of key components of the prototype solutions, various operations are performed that are aimed at acquiring data on the specific parameters of the technical components, subassemblies, and modules. Simultaneously, the procedures are carried out to identify dependencies between modules, technical parameters, and functional requirements [13]. Based on data collected in a database or expertise, potential failures and defects are forecasted. The relationships between the components, subassemblies, modules or computer procedures and failures and faults are determined using dependence graphs. These diagrams are also used to organise information and indications about which causes are responsible for a specific effect and what are the relationships between the causes. Based on a set of identified potential failures, faults, and insufficient functionality, a set of research methods is created which should be performed to verify the correctness of the operation of the prototype.

For each method, a set of measurement techniques is assigned, including test equipment and measurement methods. The number and, in some cases, the frequency of test and verification are determined. After taking into account the time constraints and cost scenarios, prototype test scenarios ("critical path" in the diagram) are generated. On this basis, decision tree diagrams are created. Experts responsible for carrying out the tests, verification, and development, based on selected, optimal scheduling of tests, develop plans for experiments. The experimental results are used to verify the hypothesis.

7. Areas of prototype testing

Prototype testing methodology applies to the full range of prototyping and takes into account the activities carried out at the stages of design, construction, functional verification, and the operation of the machine or device (Fig. 3).

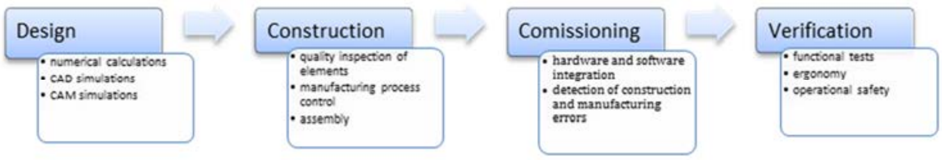

Fig. 3. Areas of prototype testing

Design includes activities related to the formulation of guidelines and the conceptual development of a prototype, represented as a mathematical model or by using a virtual construction and technological documentation. The design highlights the stage of the initial concept, the construction of the model, and the development of the process of building a physical prototype. Prototype testing at the design stage refers to the mathematical simulation model of a structure or calculations made based on a virtual model constructed in CAD. Elements of the prototype tests are also the simulations of machining processes using CAM systems.

In the process of building a physical prototype, the production stage and commissioning phase are important for further functional studies.

Manufacturing is regarded as a process in which the production of previously designed components is carried out, the assembly of machine parts is made, commercial components are purchased, and the modules of mechanical, electronic, electrical, optical, and other systems are formed. Prototype tests performed during the production relate to quality inspection on manufactured components and the monitoring of the manufacturing process. The manufacturing process is verified conditionally, only in the case of quality defects identified in the investigated objects. Verification of the technological process only applies to the range associated with product quality. Issues of cost, efficiency, logistics, safety, ergonomics, and others are ignored. The evaluation of the prototype conducted at the manufacturing stage is made according to the criteria of good, bad, or to be corrected. Particularly important is the correct classification of the defects deemed repairable by evidence. Considering expenses on the manufacturing of the element with known defects, it is necessary to consider modifications of the construction in such a way as to enable the use of the test piece, despite the identified deviations and inaccuracies.

The assembly of the unit is the first verification of the physical effects beyond the scheduled scope of the prototype tests. During the assembly, in a spontaneous manner, there all structural weaknesses are shown that have not been identified in the standard process of quality control and in the earlier stages of testing of the virtual model. This particularly applies to construction errors involving the mutual dimensional mismatch of mated elements.

Commissioning is performed after assembly and concerns the work to achieve a functioning solution, where there is the integration of mechanical, electronic, and software systems into a working, drivable prototype of a stand-alone device or functional module. Commissioning is part of the prototype test characterised by spontaneous, unplanned detection of errors and construction non-conformities or conditions that prevent the first start-up of the device. The approved plan defines the order of checks on the operation of individual modules and starting the entire system, which requires cooperation between the modules and non-autonomous systems installed. The first launch of the device is directed to obtain and confirm the fact that the technical operation of the complete system is possible, without performing evaluations related to the performance. This means that the runtime verification allows one to determine if it works but not how effectively it works. The quality of operation is an essential subject of the functional verification of a prototype device or module.

Functional verification is part of the prototype tests performed after starting, but before introduction for operation. It applies to the planned tests of a complete, running machine. In functional studies, the measurement results are verified and the assessment of in terms of ergonomics and safety in operation are performed. Functional verification is a separate stage in the process of prototyping, which determines the final level of the solution.

Examples of testing prototypes using the developed methodology are presented in publications [11, 12, 13].

Conclusion

The developed methodology allows for the determination of general and technical parameters of the prototype and its specific features which characterise the elements, components, modules, or computer procedures and then to assign the type of test to be carried out to get at the intended level of confidence that will ensure proper operation of the prototype solution. For each identified item, component, module, or computer procedure, there should be obtained the fullest information on their failures or impact on the expected functionality.

Performed evaluation of the prototype is a multi-level operation, conducted iteratively in successive phases of the development of the prototype. The subjects of evaluation are components of the device located at different levels of the complexity of the tested solution. Fractional properties, features, functions, etc. characteristic for the selected item are assessed. Tests can be multiplied, depending on the available methods for verification of the assessed level of development of the device. Final evaluation refers to the completed stage of development of the machine that is the design, manufacturing, and operation of the prototype. Performance of the final assessment, as in the case of partial evaluation, is an iterative process, carried out as part of a feedback loop until the fulfilment of required parameters, consistent with the specification of requirements of the customer, underlying the design assumptions.

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Metodyka badań jednostkowych i unikatowych obiektów technicznych

Słowa kluczowe

Badania prototypów, dekompozycja, prototypowanie, weryfikacja.

Streszczenie

Osiągnięty poziom metod projektowania i wytwarzania urządzeń technicznych umożliwia szybkie wyprodukowanie w pełni funkcjonalnego prototypu lub urządzenia jednostkowego. Wymagana efektywność procesu prototypowania wprowadza potrzebę stosowania metodyki badań prototypów wykorzystującej zasoby wiedzy zgromadzone w bazie danych historycznych problemów konstrukcyjnych, badawczych, uruchomieniowych i wdrożeniowych.

W artykule przedstawiono opracowaną w Instytucie Technologii Eksploatacji metodykę badań jednostkowych i unikatowych obiektów technicznych wspomagającą prototypowanie nowych rozwiązań zaawansowanych urządzeń innowacyjnych.

Celem przeprowadzonych prac było opracowanie rozwiązania w postaci systemu badań prototypów umożliwiającego sterowanie procesem badań w sposób oparty na zasobach zgromadzonej wiedzy dotyczącej projektowania, uruchamiania i wdrażania zaawansowanych technicznie urządzeń wykonywanych jednostkowo lub małoseryjnie. Wykorzystanie metodyki badań zwiększa gwarancję budowy prototypowych maszyn i urządzeń charakteryzujących się lepszą jakością i niezawodnością w stosunku do rozwiązań bazujących jedynie na wiedzy nabytej i doświadczeniu uczestników zespołu realizacyjnego. Metodykę badań pilotowo zastosowano w odniesieniu do kilkunastu prototypowych urządzeniach zaprojektowanych i wykonanych w Instytucie Technologii Eksploatacji.