Modification of Physical Effect Model for the Synthesis of the Physical Operation Principles of Technical System

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Abstract. Nowadays the task of initial design stages automation (stages of the technical specification and technical proposal) of new technical systems and technologies and prediction for making decisions about the operation principle and the structure of the design object is very actual. This study is dedicated to increasing the efficiency of synthesis the physical operation principle for technical systems. The proposed solutions can improve the quality of the synthesized structures of the physical operation principle by reducing the number of physically unrealizable structures. We propose the modification of the physical effect model for upgrading the quality and quantity of compatibility conditions of physical effects, and developed a method of construction the linear and network structures of the physical operation principle. The proposed models and algorithms are implemented in the developed automated system.

Keywords: Physical effect, physical phenomena, design of technical systems, operation principle of technical system, physical operation principle.

1 Introduction

Today the task of initial design stages automation (stages of the technical specification and technical proposal) of new technical systems (TS) and technologies and prediction for making decisions about the operation principle and the structure of the design object is very actual. Among the methods of realization of the first stages of design there is one of the most perspective methods connected with the using of the structured physical knowledge in the form of physical effects (PE) [1,2] for automation synthesis and choosing physical operation principle (POP) of the technical system. POP [3] is a structure that shows the connection between physical effects, whose combination leads to realization of the TS function. The rules of the POP structures of are determined by description components of the PE.

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Nowadays there is a set of methods for creating conceptual models of the physical effects describing, model formalization and creating automation systems based on them. Such methods are: the theory of inventive problem solving (Altshuller G.), a combinatorial method for finding the operation principles (Glazunov V.), the energy-information model circuits and method of parametric structural diagrams (Zaripov M.), design method for machine, device and apparatus construction (Koller R.), computer-based searching design (Polovinkin A.), and others. There are some automation systems based on this methods: "TechOptimizer" [4], "IHS Goldfire" [5], "Novator" [6], "Intellect" [7], "IdeaFinder+" [8], "TRIZ-generator of ideas" [9], etc.

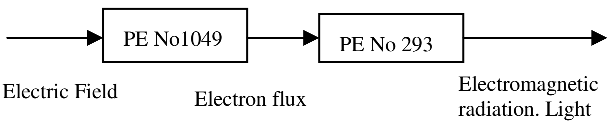
The science school was formed during the process of solving the problems of the initial stages design automation at the Volgograd State Technical University. At the CAD/CAE Department the united model of PE description and PEs database [1] that contains knowledge of different physics domains were created. The set of systems that operates with knowledge in the PE form was developed: automated system for support the process of PE database forming [10,11]; automated information retrieval system (AIRS PE) [2]; automated system for synthesis of the linear structures of the physical operation principles [3].

Example of the POP synthesis: "How can we improve the characteristics of the cathodoluminescence light sources?" [12].

The cathodoluminescence light sources based on the principle of the excitation phosphors by the electron beam. So the task for the synthesis of physical operation principle of has the following structure:

- Input cause-action: Electric field;
- Output effect-action: Electromagnetic radiation. Light;
- Limitations: The length of the PE sequence at the POP structure $\leq$ 2, it is necessary to use the PE No 293 "Cathodoluminescence"

We mean that the physical operation principle is a structure of the compatible and integrated PEs that provides the transformation of the input cause-action to the output effect-action.



PE No. 1049 "Field electron emission of carbon nanotubes", PE No. 293 "Cathodoluminescence"

Fig. 1. Example of the POP synthesis

As a result of the analysis of information systems that use the structured physical knowledge for automation of the initial stages of TS design the limitations that prevent the effective using of such systems were found:

- The requirements for the POP synthesis is limited by the parameters of the input and output actions only.
- Existing approaches, and technical solutions based on them, cannot be effective because they do not allow to use the structural transformation of the PE object.

- In the existing automated systems of the POP synthesis the algorithms for verification of POP physical reliability are proposed at a qualitative level but there is no verification at the quantitative level.
- The missing of developed method the network POP structures synthesis a very important problem.

The aim of this work is to decrease the percentage of manual design the technical solutions and increase the efficiency of the synthesis of POP structures. The evaluation the efficiency of the synthesis of POP structures uses a number of physically realizable solutions.

2 Modification of the Physical Effect Model

Existing algorithms for the synthesis of POP structures that were created earlier use the three-component structure of the PE description: $F_i = (A_i, B_i, C_i)$, where A_i – input cause-action of PE; B_i –object of PE; C_i – output effect-action of PE.

Example of PE: No. 293 "Cathodoluminescence":

- A – The flow of electrons. Particle energy.
- B – Phosphor.
- C – Electromagnetic radiation. Light. Brightness.

But this structure is not good for verification the compatibility of the physical effects where the object experiences big structural transformations:

- transformations of the aggregate state (melting, crystallization, evaporation);
- transformations of the electrical structure (semiconductor-metal transition);
- transformations of the magnetic structure (paramagnetic-ferromagnetic), etc.

This is a significant defect, so using the four-component structure of the PE description for synthesis of the POP structures is suggested:

$F_i = (A_i, B^1_i, B^2_i, C_i)$, where A_i - PE input cause-action; B^1_i - the initial state of the PE object; B^2_i - the final state of the PE object; C_i –PE output effect-action.

Example of PE: No. 30 "Degaussing heating".

- A – Temperature. The increase to the Curie temperature or higher.
- B^1 – Ferromagnetic.
- B^2 – Paramagnetic, antiferromagnetic.
- C – Magnetization. Decrease to zero.

The methods used in the existing automated system (SAPFIT) [2] were chosen as algorithmic base for solving problems of POP structures synthesis because this system is shown very good results. According the analysis of the PE database there are a lot of physical effects where the values of physical quantities are presented not as a numeric but as text description. This method of defining the physical quantity complicates the use of PE in quantitative conditions of compatibility. To solve this problem, it was decided to modify the existing model of PE description with adding to the parameters of the input cause-actions and output effect-actions the physical quantity represented in the form of linguistic variable.

It seems appropriate to normalize the values of all physical quantities to a common scale [0, 1]: 0 - minimum value; 0.1 - very small; 0.3 - small; 0.5 - medium; 0.7 - great; 0.9 - very large; 1.0 - maximum value.

Normalizing the values of all physical quantities to a single scale is possible due to the insertion of a linguistic variable. All the set of values of physical quantities can be divided into three terms of linguistic variable: “Small value”, “Average value”, “Large value”.

To normalize the values of physical quantities corresponding the value of linguistic variable “Small” authors use the Z-shaped membership function.

$$f_Z(x;\, a,\, b) \;=\; \begin{cases} 1, if \;\; x \le a \\ 1 - 2(\dfrac{x-a}{b-a})^2, if \;\; a \le x \le \dfrac{a+b}{2} \\ 2(\dfrac{b-x}{b-a})^2, if \;\; \dfrac{a+b}{2} \le x \le b \\ 0, if \;\; b \le x \end{cases}, \tag{1}$$

where a = 0.1, b = 0.9.

To normalize the values of physical quantities corresponding the value of linguistic variable “Large” authors use the S-shaped membership functions.

$$f_S(x;\, a,\, b) \;=\; \begin{cases} 0, if \;\; x \le a \\ 2(\dfrac{x-a}{b-a})^2, if \;\; a \le x \le \dfrac{a+b}{2} \\ 1 - 2(\dfrac{b-x}{b-a})^2, if \;\; \dfrac{a+b}{2} \le x \le b \\ 1, if \;\; b \le x \end{cases}, \tag{2}$$

where a = 0.1, b = 0.9.

To normalize the values of physical quantities corresponding the value of linguistic variable “Average” authors use the П-shaped membership functions.

$$f_{\Pi}(x;\, a,\, b,\, c,\, d) = f_z(x;\, c,\, d) * f_s(x;\, a,\, b), \tag{3}$$

where a = 0.1, b = 0.4, c = 0.6, d = 0.9.

As a result of the insertion functions we can assign each physical quantity a certain value from interval [0, 1].

3 Modernization of Qualitative and Quantitative Conditions of the Physical Effects Compatibility

Two consecutive PEs $F_i = (A_i, B^1_i, B^2_i, C_i)$ and $F_{i+1} = (A_{i+1}, B^1_{i+1}, B^2_{i+1}, C_{i+1})$ are compatible if the output effect-action of the PE C_i matches the input cause-action of following PE A_{i+1}. We can see the physical operation principle in Fig. 2.

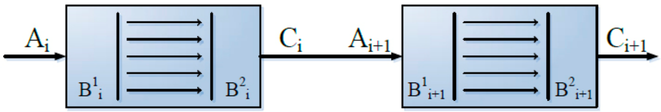


Fig. 2. Fragment of the structure of the physical operation principle

Existing conditions of the PE compatibility:

- Type of output action C_i matches the type of input action A_{i+1};
- The name of the output action C_i matches the name of input action A_{i+1};
- Qualitative characteristics of the output action C_i match the qualitative characteristics of the input A_{i+1};
- if output action C_i and input action A_{i+1} are parametric the physical quantities C_i matches the physical quantities A_{i+1} and B_i object matches the object B_{i+1}.

Modification of the qualitative conditions of compatibility achieved by use the feature transform of the physical quantities. Feature transform of the physical quantity can take the following values:

- change: increase; decrease; not monotonous; intermittent;
- constant;
- not determined.

If feature transform of the physical quantity C_i matches with feature transform of the physical quantity A_{i+1} we conclude that the F_i and the F_{i+1} are compatible from point of view the transformation of physical quantity.

Also the modification of the qualitative conditions of compatibility is achieved by use the initial and final states of the PE objects: if the B_i and the B_{i+1} objects have structural transformations we define 3 possible combinations:

1. Objects B_i and B_{i+1} without structural transformation. In this case the structure of each PE object will be the following: the number of phases; the structure; type of contact, type of mixture. If the values of B_i and B_{i+1} are the same we can conclude that these effects are compatible by structure. If the stage of analyzing B_i and B_{i+1} compatibility is completed successfully, we should verification the compatibility of F_i and F_{i+1} in each phase which is a part of the object: phase state; chemical composition; magnetic structure; electrical conductivity; mechanical status; optical status; special characteristics. If the features of the B_i and B_{i+1} are the same in each phase we can conclude that F_i and F_{i+1} are compatible.
2. Objects B_i and B_{i+1} with the structural transformation. In this case it is necessary to compare the final state of the object B^2_i and the initial state of the object B^1_{i+1} for the compatibility analysis of the F_i and the F_{i+1}. The process of the state comparing of B^2_i и B^1_{i+1} is described at the previous paragraph.
3. One of the objects is without structural transformation, but another one has a structural transformation. This combination is a special version of event when both B_i

and B_{i+1} have a structural transformation. The only difference is that the PE object without structural transformation is described as PE object with a structural transformation and the initial and final states are identical.

Then the quantitative conditions of the compatibility are formulated. In existing systems of the POP synthesis there is no compatibility verification at a quantitative level. This disadvantage is important in evaluating of the PE compatibility and, in addition, in the quality evaluation of the synthesized POP structures. In conditions of PE compatibility at the quantitative level we will consider the range of variation of the physical quantity. There are four possible combinations for setting the values of the physical quantities C_i and A_{i+1}:

1. Physical quantities C_i and A_{i+1} are given as numeric value. In this case compatibility F_i and F_{i+1} at the quantitative level requires a common interval of the values ranges of the output action C_i and input action A_{i+1}. If there is a common interval we can conclude that F_i and F_{i+1} are compatible quantitatively.
2. Physical quantities C_i and A_{i+1} are given in the form of linguistic variable. Consider two situations to verify the F_i and F_{i+1} compatibility:

- The physical values of two PEs are located in partition areas of linguistic variable without common border ("Small" and "Large"). In this case it can be concluded that F_i and F_{i+1} are incompatible;
- The values of the physical quantities of the two physical effects are located in the same or neighboring partition areas of linguistic variable. In this case it need to verify the inequality:

$$\mu(F_i) - \mu(F_{i+1})| \leq \varepsilon, \tag{4}$$

where $\mu(F_i)$, $\mu(F_{i+1})$ – the value of the membership function of the physical quantity; ε - the value that specifies the maximum value of the difference of membership functions F_i and F_{i+1} and defines before the synthesis of POP structures.
If the inequality it can be concluded that F_i and F_{i+1} are compatible with quantitative conditions.

3. Physical quantity of one PE defines as numerical value and the other PE - in form of linguistic variable. This situation is a special event when the values of physical quantities F_i and F_{i+1} are defined in the form of linguistic variable. In this case to verify of compatibility F_i and F_{i+1} at quantitative level needs the numeric value of the physical quantity represented as the corresponding values of the membership function on the interval [0, 1]. The analysis of the F_i and F_{i+1} compatibility is described at the previous paragraph.
4. Physical quantity of at least one PE is not specified. In this case it is possible to implement two strategies:

- Strategy of PEs compatibility for completeness - if the physical quantity of at least one PE is not specified the F_i and F_{i+1} are compatible at the quantitative level. With implementation of this strategy total number of compatible PEs increases, however the quality of the synthesized POP structures is reduced;

- Strategy of PEs compatibility for accuracy - if the physical quantity of at least one PE is not specified the F_i and F_{i+1} are incompatible at the quantitative level. With implementation of this strategy the quality of the synthesized POP structures increases, but the number of compatible PEs and therefore the total number of synthesized POP structures decreases sharply. The main disadvantage is the loss of a number of strategies implemented POP structures.

  The number and quality of the POP structures will be different depending on user selection of one of two developed strategies.

4 Methods of POP Structures Synthesis

Formulated on the basis of the new qualitative and quantitative conditions of PEs compatibility was developed algorithm for generate the transition graph (in Fig. 3).

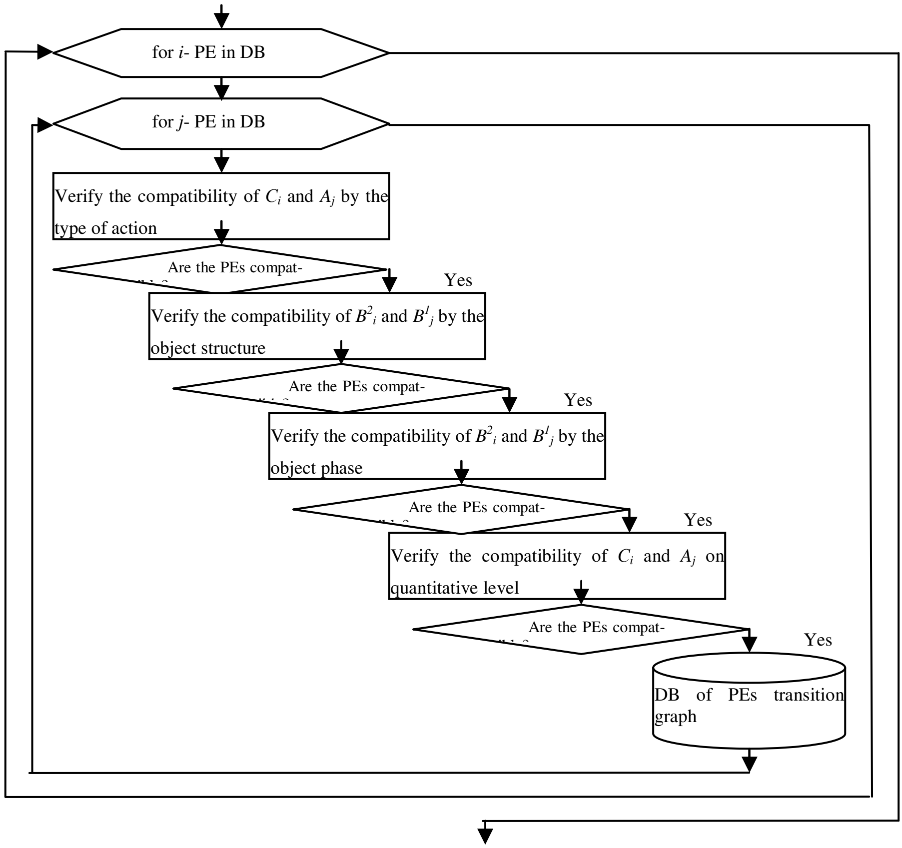


Fig. 3. Algorithm of generation of the PEs transition graph

Our proposed changes of the PEs compatibility conditions led to modifications of existing methods of synthesis of POP structures which made it possible to formulate a new model for linear POP structures.

In order to improve the adequacy of the synthesized POP structures we take into consideration the set of PE input cause-actions that allow design the original method of network POP constructing.

Consider our proposed methods of designing POP structures more detail.

4.1 The Method of Linear POP Structures Synthesis

Verbal description of the method is following:

1. The length of the POP structures is set.
2. The required input and output parameters of the POP structure are set. If input cause-action or output effect-action is not set the POP synthesis is not possible.
3. If necessary we set the prohibited and required physical effects for synthesis of POP structures. If the structure of the synthesized POP uses prohibited effect it will be removed from the list of possible transitions from an input cause-action to a output effect-action. If the structure of the synthesized POP does not use required effect it is also removed from the list of possible transitions.
4. Sets the type of PEs compatibility conditions (quantitative or qualitative/quantitative) and loaded the table of PE compatibility. The oriented graph of the PE compatibility based on the table is built. PEs are the vertices of the graph. If the transition from one PE to another is possible then the arc is built between vertices.
5. For each PE with initial synthesis conditions the finding of the compatible PE is realized. If the current number of the processed transition is less the length of the PEs sequence of the synthesized POP structure then on the basis of the transition graph is defined the list of PEs which are compatible with the processed physical effect. The search of the compatible PEs is realized for each physical effect from the list. This steps is repeated until the current number of the processed transition is not equal the length of the sequence of the synthesized POP structure.
   If the length of the synthesized POP sequence and the current number of processed transition have the same values then further verification is performed of whether or not processed PE is satisfied by final conditions of POP synthesis. In the case of a positive result the current temporary structure is added to the list of synthesized POP structures as one of the possible transitions from input cause-action to the output effect-action. Otherwise this structure of the synthesized POP is not satisfied to the final conditions of the POP synthesis.
6. If at least one linear structure is created successfully we can conclude that the POP synthesis with the predetermined parameters is possible.

4.2 The Method of Network POP Structures Synthesis

In base of the proposed approach of synthesis of network POP structures is the multiple construction of linear structures. Verbal description of the method is following:

1. The length of the synthesized POP structure is set.
2. The required input and output parameters of the synthesized POP structure are set. If input cause-action or output effect-action is not set the POP synthesis is not possible.
3. If necessary we set the prohibited and required physical effects for synthesis of POP structures. If the structure of the synthesized POP uses prohibited effect it will be removed from the list of possible transitions from an input cause-action to a output effect-action. If the structure of the synthesized POP does not use required effect it is also removed from the list of possible transitions.
4. Sets the type of PEs compatibility conditions (quantitative or qualitative/quantitative) and loaded the table of PE compatibility. The oriented graph of the PE compatibility based on the table is built. PEs are the vertices of the graph. If the transition from one PE to another is possible then the arc is built between vertices.
5. On the basis of the predetermined parameters are constructed linear POP structures. Algorithm for constructing linear POP structures described in the section "The method of synthesis the linear POP structures". If the synthesis of linear POP structures is correct we proceed to step 6. Otherwise we conclude the impracticability of synthesis POP structures with specified input and output actions.
6. Synthesized linear POP structures are analyzed for the presence of PEs that have set of input cause-actions.
7. For all effects that have set of input actions are build the additional linear structures:

- input actions are the initial input action of POP structure
- or input actions are the input actions of physical effects belonging to the linear POP structure
- and output actions are unused input actions.

8. If at least one network structure is built successfully we can conclude that the POP synthesis with the predetermined parameters is possible.

5 Evaluating of the Developed System Efficiency

Automated system of the POP structures synthesis "Assistant" using developed models and methods is a "client-server" software with .NET Framework technology. Microsoft SQL Server has been used as the database management system.

It was realized the comparative analysis of the number of the synthesized POP structures obtained as a result of the automated systems "SAPFIT" [2] and "Assistant" to evaluate the efficiency of the developed compatibility conditions. It should be noted that the automated system "SAPFIT" cannot synthesize network POP structures, so the efficiency of the automated system "Assistant" will be implemented through a comparative analysis of the number of the linear POP structure.

The test is to run the systems "SAPFIT" and "Assistant" with the same input and output parameters and comparing the results. The tests were conducted 30 times with different tasks on the synthesis of POP structures.

Table 1. Comparative analysis of the synthesized POP structures

Automated system	Number of synthesized POP structures		
	The length of PEs sequence = 2	The length of PEs sequence = 3	The length of PEs sequence = 4
SAPFIT	214	-	-
ASSISTANT	11	672	1640

Table 1 shows the results. Number of synthesized POP structures is a arithmetic mean number of synthesized structures obtained over 30 tests.

The results in Table 1 show that the automated system "Assistant" can significantly reduce the number of physically unrealizable POP structures.

Also in order to verify the developed system "Assistant" authors have solved the several test engineering problems, such as "How to improve the performance of cathodoluminescent light sources?" (Table 2).

Table 2. Comparative analysis of the technical problem solving

The task for the synthesis	SAPFIT	ASSISTANT
Input – electrical field; Output – electromagnetic radiation, light; The length of the PEs sequence = 2.	279	18

A detailed analysis of POP structures synthesized by automated system "SAPFIT" showed that most of them are physically unrealizable. This is due to the fact that in conditions of PE compatibility there are no compatibility verifications the feature transform of physical quantity, are not considered the structural transformations of PE objects, and are not formulated the quantitative compatibility conditions. Thus, the manual design of technical solutions decreased by increasing the efficiency of POP structures synthesis.

6 Conclusion

In study describes the improved model of PE description with adding to the existing parameters of the input cause-actions and output effect-actions of PE the physical quantity represented in the form of linguistic variable. Authors proposed the four-component structure of PE description which allows you to use the structural transformation of PE object.

Upgraded PE compatibility conditions at qualitative level allows to use the feature transform of the physical quantity. Authors introduced PE compatibility verification at the quantitative level. Developed the algorithm of generation the transitions graph based on the new PE compatibility conditions. The author's method of construction of linear POP structures uses in its algorithmic basis the modified qualitative and quantitative conditions of PE compatibility. Authors formulated the original method of constructing the network POP structures which allows to use the set of input cause-actions of PEs used in linear POP structures.

The analysis of the developed automated system “Assistant” allows made the conclusion that the quality of the initial stages of computer-aided design has increased by reducing the number of physically unrealizable POP structures.

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