Sequential analysis of variants and optimal design techniques for human-machine systems

M G Grif, S A Kochetov and N D Ganelina

Novosibirsk State Technical University, 20, Karla Marksa ave., Novosibirsk, 630073, Russian Federation

E-mail: grifmg@mail.ru

Abstract. The current paper considers automatic design of functioning processes of human-machine systems. The idea of models, methods and techniques that are discussed in the article is based on functional-structural theory and the generalized structural method, which was suggested by prof. A.I. Gubinsky. The process of functioning is presented as a sequence of simple operations - basic functional units, which can be combined into basic functional structures. Efficiency, quality and reliability of the functioning process are considered as local criteria in optimization problems. Basic design strategies for human-machine systems are given: a down-top, top-down approach and their combination. A definition of a system operation process as a notation based on binary relations between elements included in a functional net is presented. A special algorithm to determine whether a functional net defined as a set of binary relations between net elements can be reduced to a superposition of basic functional structures is stated. All alternative processes of operating of a human-machine system are formed by an alternative graph and its traversal ways. A directional search algorithm is applied to finding the optimal solution. It allows building partial solutions step-by-step. For equal (repeated) segments of a functional net the alternative graph is changed and solutions are produced by the specific optimized technique.

1. Introduction

Activities and information processed in the modern world constantly increase. Techniques for definition and evaluation of functioning processes (FP) in complex human-machine systems (HMS) become more relevant. Decision support systems help people to process a large amount of information, find a set of possible solutions and evaluate consequences of decisions, justify the solution. Considering HMSs results in particular optimization problems with criteria different by nature. This also requires to evaluate all possible alternatives for certain process segments. One of the universal instruments to describe, assess and optimize an operating process is applying functional nets, functional-structural theory (FST) and the generalized structural technique (GST) that was suggested by prof. A.I. Gubinsky [1]. This approach was developed in [2,3]. Techniques based on FST for the sequential optimization of HMS FP were offered. Efficiency, quality and reliability criteria (EQR) were used to evaluate solutions. EQR probabilistic criteria of a functioning process of a HMS are calculated via a probabilistic graph, which is reduced (enlarged) according to special rules. The parameters included are the following: $B$ is a probability of correct (without mistakes) execution, $T$ is an average run time and $V$ is an average expenses or revenue of the process fulfillment.
2. Functioning process definition and design techniques

A HMS functioning process is a logical and time sequence of actions and operations performed by ergatic and non-ergatic system elements. This sequence of operations is steady to disturbances, and results in achieving a goal (s) of functioning [4-6]. A functioning process is presented as a functional net. And the net is a set of operations \( O \). We determine an operation \( O = O(F, E, S, Q) \) as a process of the function fulfillment \( F \) performed by the element \( E \) in the state \( S \) of the HMS. \( Q \) is for efficiency, quality and reliability of the HMS process. An operation \( O \) can be simple (named basic functional unit - BFU) or include several other operations. Combinations of BFUs, which are applied frequently and have mathematical models evaluated in advance, are called basic functional structures (BFS). Examples of BFU are the following: 'work operation' (WO), 'functional check' (FC), 'diagnostic check' (DC). BFSs are: 'sequential work operation', 'work operation followed by functional check', etc. Each of HMS functional processes is defined as a superposition of basic functional structures \( O = BFS\left(O_{1}, O_{2}, ..., O_{n}\right) \). BFS \( \in M_{BFS} \), \( O_{i} \) is a simple or composite operation. Two operations with the same concurrent function \( F \), \( O(F, E_{1}, Q) \) and \( O(F, E_{2}, Q) \), are alternative ('parametric') variants for the execution of operation \( O \), as well as compound operations \( O_{BFS}\left(O_{i_{1}}, O_{i_{2}}, ...ight) \) and \( O_{BFS}\left(O_{s_{1}}, O_{s_{2}}, ...ight) \), are 'structural' alternatives.

There are two strategies for a HMS FP design.

The first one is a 'top-down' design strategy. Applying this strategy a functional net is considered as a combined operation and a superposition of a set of alternative realizations. In this case a user describes a set of alternative HMS processes by an alternative graph (AG) (figure 1).

![Figure 1. An alternative graph for a HMS FP.](image1)

The second strategy is a 'down-top' approach, when a functional net is explicitly presented as a sequence of operations or workflow (figure 2).

![Figure 2. Explicit presentation of a HMS FP.](image2)

The top-down strategy was implemented in a hybrid expert system HES INTELLECT-2 [3] that was further developed into the HES INTELLECT-3 [2]. The current version of the HES offers options to design functional nets both with top-down and down-top strategies as well as with their combination.
Improved graphical interface is another advantage of the system. There is an option to design a functional net explicitly, to add an alternative segment into a functional net, where the segment is confined to two edges. It's also possible to build all isomorphic representations of an alternative graph and to run a certain directional search in an automatic or manual mode. The range of functional net elements was enlarged by a new composing element 'transit AND'. It denotes the end of any functional unit and the beginning of the next one. In figure 2 this element is labeled as $T_i$. Composing elements $H$ and $K$ were included to mark the end and the start point of functional nets. The beginning and the end points of parallel operations also have special composing elements.

Functional nets were described as a set of binary relations $\{O_1, O_2, \ldots, O_{n-1}, O_n\}$ between net elements, where $O_n$ follows the $O_{n-1}$. An example of the definition of a functional net (the net is presented in figure 2) as a set of binary relations is illustrated by the equation (1):

$$R_{BS} = \{ (H, T_1), (T_1, A_1), (A_1, T_2), (T_2, A_2), (A_2, T_3), (T_3, \beta_f), (\beta_f, A_2), (T_4, K) \}.$$  

(1)

In order to optimize a functional net and to evaluate its indexes (efficiency, quality and reliability) it is necessary to have a definition of a functional net as a superposition of BFSs. However, a HMS FP representation as a set of binary relations between elements of the net didn't guarantee the net could be built as a superposition of structures. The superposition form for the functional net presented in figure 2 is shown in figure 3.

![Figure 3](image-url)

**Figure 3.** A functional net as a superposition of BFSs.

The HES INTELLECT-3 provides an automatic transformation of a FN sequential form into a superposition of BFSs. While this transforming a BFS is replaced by the 'equivalent work operation' (WOeq) with the same EQR indexes the original BFS had. Equivalent work operations are indicated by negative numbers.

A functional net in the HES INTELLECT-3 can be designed in a graphic mode or formally by symbols. In the second case the system provides parsing for the input sequence and analyzing whether this functional net can be presented as a superposition of BFSs. To perform this analysis the INTELLECT-3 applies a down-top technique of parsing - 'convolution-transfer' [7-9]. A functional net, presented as a superposition of structures, can be described as a generative grammar $G = \langle T, N, P, S \rangle$, where

- $T$ is a set of terminal symbols that includes the whole subset of basic functional units and composing elements;
- $N$ is a set of non-terminal symbols, those are all kinds of basic functional structures and equivalent work operations;
- $P$ denotes grammar rules generating all kinds of BFSs from terminal symbols $BFS(1) \rightarrow \alpha_1, BFS(2) \rightarrow \alpha_2, \ldots, BFS(n) \rightarrow \alpha_n$, where $\alpha_1, \alpha_2, \ldots, \alpha_n$ are strings of terminals if $\alpha_1 \neq \alpha_2, \ldots, \alpha(n-1) \neq \alpha_n$, and a rule is $WOeq \rightarrow BFS(1) | BFS(2) | \ldots | BFS(n)$. A BFS type is indicated in parentheses;
- $S$ is the initial symbol of the grammar, $S \rightarrow WOeq$.

The algorithm determining whether given functional net can be reduced to a superposition of BFSs
is based on forming a stack and includes the following steps.

1. In the 'transfer' operation each next terminal symbol from the input string is taken out and placed into the stack.
2. All cells and their content (symbols) are scanned from the top of the stack to the number N (or to the last one). If the symbol doesn’t match with any of right-hand sides of production rules (which means that this content is not isomorphic to a set of a certain kind of BFS), then the algorithm moves to step 1. In other case the current set obtained is analyzed whether it includes feedback loops of functional or diagnostic checks. If the next convolution operation breaks a feedback loop the algorithm returns to step 1. The convolution of all symbols from the top to N is made (step 3) when all conditions are met.
3. During 'convolution' operation a set of symbols in the top of the stack is replaced by a non-terminal symbol from a left-hand side of a production rule. This non-terminal symbol is put at the top of the stack from a set \( \{ \text{WOeq, BFS(1)} | \text{BFS(2)} | \ldots | \text{BFS(n)} \} \).
4. Moving to step 2.

The algorithm ends when the input string of terminal symbols is empty. The operation is successful if the algorithm results in a non-terminal symbol \( S \) in the stack.

3. Optimization techniques for HMS FP

The optimization problem (the generalized problem of dynamic programming) is stated as follows:

\[
K_{EQR}(A) \rightarrow \text{extr}, A \in M_d \subseteq M_a.
\]  

where \( K_{EQR}(A) \) is the optimal criterion for a combination of EQR criteria; \( M_d \) – a set of feasible alternatives, alternative variants for the process – \( M_a \) [2].

The method for the serial optimization of HMS FP based on the FN model under the general scheme for the method of serial analysis of variants with a stepwise design of partial solutions [10-11] is implemented in the HES INTELLECT-3. The algorithm of a stepwise design is defined by the rule for selecting partial solutions (subnets) \( \mathcal{G} \), which should be developed at each step, and a set of tests \( \xi \) that eliminate the subnets which can not be completed to the optimal ones. A set of tests \( \xi = \xi_1 \cup \xi_f \) consists of the requirements for the optimum solution (\( \xi_o \)) and feasibility (\( \xi_f \)) for partial solutions. These conditions depend on the type of the optimization problem. The general scheme of the directional search algorithm (DSA) for a FN within the technique of the consecutive analysis of alternatives is the following:

\[
\text{DSA} = \hat{\xi}_o (y_1), \mathcal{G}(x_1), \hat{\xi}_f (y_2), \mathcal{G}(x_2), \ldots, \hat{\xi}_o (y), \mathcal{G}(x), \hat{\xi}_f (O).
\]

where \( y_j = O_k \) is a chosen operation \( O_k \).

The transformation of a sequential form of a functional net into a superposition of BFSs is performed before the directional search algorithm starts. An alternative graph describing a superposition of BFSs can include repeating nodes which duplicate the same segment of the functional net. An example of a functional net with alternative segments is presented in figure 4.
Figure 4. FN with an alternative segment.

An alternative graph for the net presented in figure 4 is shown in figure 5. Identical nodes 1 and 2 can be seen in the figure.

![Alternative graph for a FN with an alternative segment.](image)

Figure 5. Alternative graph for a FN with an alternative segment.

The directional search algorithm applied to find the optimal solution on such alternative graph with duplicating nodes leads to repeating calculations $\xi(x), \delta(y)$. If a functional net consists of multiple alternative segments, then a slowdown in finding solutions is significant. The HES INTELLEKT-3 offers a modified technique to determine the optimal variant of the net operating by reducing calculations. Before the directional search starts the system analyzes a functional net in order to detect equal parts of subnets [3]. Alternative graphs for functional nets of this kind don't contain identical subtrees, their nodes are particularly marked instead (figure 6).

![Alternative graph for a FN with common parts.](image)

Figure 6. AG for a FN with common parts.

The directional search algorithm was adopted to apply a new type of alternative graphs. If EQR indexes are evaluated in a node that is defined as equal to another one, the partial solution found in this node is retained. If the DSA at the next step needs to calculate indexes in the marked node, which has been evaluated earlier, this solution is taken from those previously memorized.

In the HES INTELLEKT-3 there is an opportunity to control traversals in the directional search algorithm. While designing a functional net it is possible to set a certain traversal. Another option is to generate traversal variants automatically. In the automatic mode a rough estimation of the time to resolve the problem with a certain chosen sequence is determined [2].
4. Conclusion

The paper considers models, methods and techniques for automatic design of functioning processes of human-machine systems. The approaches are based on functional-structural theory and the generalized structural method that was suggested by prof. A.I. Gubinsky. Methods for describing a HMS functioning were discussed, such as an alternative graph representing a superposition of functional nets and a set of binary relations between elements of a net. The top-down and down-top strategies for a HMS design were presented.

The general scheme for finding the optimal solution considering all alternative segments of functioning is presented. A directional search algorithm is applied to finding the optimal solution. It allows building partial solutions step-by-step. For equal (repeated) segments of a functional net the alternative graph is changed and solutions are produced by the specific optimized technique. The hybrid expert system developed to design human-machine systems allows one to build all isomorphic representations of an alternative graph, generate the specific directional search algorithm automatically and manually, as well as to combine all three design strategies.

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