Real-time distributed computing system for modeling of physical processes

V Bychkov¹, N Dembitsky²

¹M. V. Lomonosov Moscow State University, Moscow, Russia
²Moscow Aviation Institute (National Research University), Moscow, Russia
E-mail: bychvl@gmail.com

Abstract. Modern physical experiment imposes stringent requirements on the speed of computing devices built into an experimental setup. The purpose of them is to manage the simulated processes in a timely manner synchronized with the rate of parameters change. Coordinated by the interaction of physical and computational processes in the experiment most often determines the receipt of adequate results. At developing of control systems for experimental installations, not only calculations of functional characteristics and dependencies are required, but also a logical analysis of the input information. Survey of a large number of sensors, the need to control numerous devices and physical installations results in an avalanche of the software growth, slowing down information traffic, and increasing of the computing load on computers. All this complicates the task of coordinating of computational and physical processes in the experiment, and reduces the reliability of control systems. The proposed approach to increasing the efficiency of computing systems is based on the distribution of computers within the experimental setup. Methods of continuum computing devices embedding into the control of interacting processes and their transformation into one of the links in the system are considered. On the basis of continuum processors, a hardware implementation of a distributed knowledge processing system is created, which is built into the complex of control and management tools for complex experimental installations.

1. Introduction

Improving the reliability of complex experimental facilities (EF) operation is based on information about the current and forecast state of physical processes. The completeness of control of technical objects is estimated by the formula [1,2]:

\[ \nu = \frac{\lambda_k}{\lambda_o}, \]

where \( \lambda_o \) is the failure rate of the control object, and \( \lambda_k \) is the failure rate of the controlled part of the control object. For highly reliable EF, equipment is considered to be inoperative if at least one of the functional characteristics is outside the permissible limits [3]. Therefore, they require the introduction of automated integrated diagnostic and control systems (EDCS). In EDCS EF, it is necessary to ensure, along with the completeness of control, the speed of decision-making, which guarantees timely diagnosis of dangerous situations. The use of distributed computers makes it possible to solve both problems, ensuring the reliable operation of complex EFs.
2. Formulation of the problem

In complex experimental equipment, functional-algorithmic control systems (FAS) process a continuous stream of data on the characteristics of processes. FAS process models combine analytical calculations with logical link analysis.

For logical analysis in control and diagnostic systems, artificial intelligence methods based on knowledge processing are effective \(^4\). Such systems perform a cyclic scanning of rules and facts \(^5\), which requires a large amount of computing resources and time-consuming data exchange between sensors and computing devices \(^7\).

A generalized mathematical model of a workable EF is the \(N\)-dimensional domain \(Q\), inside which all the functional characteristics \(F = \{f_1, f_2, \ldots, f_N\}\) of physical processes should be located:

\[
\forall f_i \in F : \{f_i(x_1, x_2, \ldots, x_M, t) \notin Q, i = 1 \div N, \forall \exists \in X, \exists \in \Theta\}, \tag{2}
\]

where \(\Theta\) is the domain of characteristics, \(X = \{x_1, x_2, \ldots, x_M\}\) – is the set of process parameters and stimulating signals of the functional control system. The model determines the relationship between the source data and the procedures by which information is processed.

The network model of the computing process determines the relationship between the source data and the procedures by which information is processed. On the set of functions \(F_i \subset F\) for the \(i\)-th FAS mode of operation and the set of parameters \(X\) of the display \(\Delta\) and \(\Gamma\) we define:

\[\Delta(F_i) \subset X\] and \[\Gamma(X) \subset F_i\].

The map \(\Delta\) defines for each function \(F_i\) the set of input data \(\Delta(F_i) \subset X\), necessary for its execution. The map \(\Gamma\) determines for each parameter \(F_i\) the set of functions \(\Gamma(x_j) \subset F_i\), that can be activated to obtain \(x_j\). Thus, the structural model of the knowledge base for the \(i\)-th FAS operation mode is a bipartite directed graph: \(H = (F_i \cup X, \Delta, \Gamma) = (F_i \cup X, R \cup E)\), in which \(F_i\) is the set of vertices corresponding to functional dependencies of parameters, \(X\) – initial data and results of parameter calculations, \(R\) – arcs from \(X\) to \(F_i\) that determine the unique correspondence of vertices from \(F_i\) to vertices \(X\), \(E\) of the arcs from \(F_i\) to \(X\), that determine the set of source data necessary to activate the \(F_i\) function.

The aim of this work is to create a distributed computer network that performs continuous monitoring of the functional characteristics of EF processes.

The proposed alternative to the built-in digital control systems, based on the use of continuous calculators, provides operational processing of information about the state of controlled physical processes and equipment of the electronic control unit. The main objective of such a system is to increase the speed of EDCS due to the decentralization and parallelization of computing.

3. Continuous computing devices EDCS

The basic element of a distributed computer network of the EDCS is a continuous computing device \(^8\) that performs continuous processing of analog signals using logical and functional transformations. Continuous computing devices (CCD) are a combination of analog and logic circuits with a unified structure of functional logic connections that solve two problems simultaneously: continuous calculation of functional dependencies and their logical analysis. Both tasks are solved jointly in a time continuum of changes in the source data. CCDs can be embedded in any system of interacting processes in the form of an adequate mathematical model and become one of the components of the EF.

The logic of the CCD operation is based on processing the relationships between the characteristics of the simulated process and can be represented as predicates:

\[i f \ \theta(x_1, x_2, \ldots, x_n, t) \land \varphi(x_1, x_2, \ldots, x_n, t) \land \psi(f, x_1, x_2, \ldots, x_n, t) \ then \ q(t) = 1\] \tag{3}

\[i f \ q(t) = 1 \ then \ r(t) = f(x_1, x_2, \ldots, x_n, t)\] \tag{4}
where \( t \) is time, \( q(t) \) is a binary function, \( r(t) \) is a calculation result, \( x_1, x_2, \ldots, x_n \) are input signals (parameters); \( \theta, \varphi, \psi \) are binary functions; \( \theta \) – verification of the conditions for calculating the process characteristics, is verification of the readiness of the initial data for the calculation, \( \psi \) – verification of restrictions on the process characteristics, \( f \) is the output function of the process model. Logic, as well as process characteristics, is considered in the continuum of time.

A feature of the operation of the CCD is the electronic key switching of the output circuit for transmitting the calculation result \( r(t) \). The CCD stops transmitting the values of the calculation function \( f(t) \) to the network if at least one of the conditions \( \theta, \varphi \) or \( \psi \) is not met, but continues to continuously influence the logic of processing the data of the system for evaluating functional characteristics by transmitting the binary function \( q(t) \). Checking the conditions \( \theta, \varphi, \psi \) and applying the key scheme at the functional output gives the process of calculations in the CCD a fundamentally new opportunity compared with the well-known analog processors FPAA (Field-programmable Analog Array) \cite{9}.

The written expressions (3) and (4) specify the process modeling mode in which its model is given by the function \( f(x_1, x_2, \ldots, x_n) \). At each moment of time \( t \), the process model is in one of two states: “PERFORMING” or “WAITING FOR PERFORMANCE”. Due to the unification of the input and output signals, the CCD can be combined into a computer network. The state of such a network continuously changes with changes in the input signals and depends on the state of each CCD included in it.

To calculate the functions \( f_1, f_2, \ldots, f_N \), the CCD uses analog interpolation of tabulated non-linear functions or processing of analog sensor signals. The rate of calculation is determined by the processing operations of analog signals (summation, integration, differentiation, division, comparison). When changing the mode, the processing speed is set by transistor keys in the control circuits, the speed of which reaches fractions of a microsecond.

4. Functional principle of a distributed functional control network

An important aspect of the construction of a diagnostic system for ED is the formation of a knowledge base. In contrast to the widespread expert systems \cite{10-15} in a distributed control system, knowledge is understood as a set of functional-logical dependencies linking the characteristics of processes in the ED with signs of failures.

In order to make a decision on the choice of the value of the function for assessing the health of an ED \( f_j \in \mathcal{F}_i \), it is necessary to perform a multivariate analysis of the processes state according to the input parameters \( X_i(t) \), since the dependence of \( f_j(t) \) on \( X_i(t) \) can be not only analytical, but also logical in the form of predicates (3), (4), which determine the conditions for choosing the function \( f_j \).

The proposed approach is based on the creation of a functional control network (FCN)
all actions are localized, which are necessary both to determine the state of processes that affect failures and to transfer functional characteristics to the system. FAS with attached CCD form a functional-logical cluster of synthesis of process status signals (Figure 1).

In its capabilities, FCN resembles a neural network that binds interacting organs in living organisms. Each CCD controls the state of the influencing processes and, when the necessary conditions are met, connects the function of checking the performance assessment. In terms of artificial intelligence systems, a cluster is an intelligent network agent.

The functional-logical cluster for estimating the parameters of the \(i\)-th control object contains \(k_i\) CCDs defining a certain information processing algorithm. The value of the parameters \(X_i(t)\) from the sensors obtained with the given stimulating signals \(\nu_1(t), \nu_2(t), \ldots, \nu_n(t)\) is continuously susceptible to the input of the cluster. The calculation conditions \(\theta(t)\) and \(\varphi(t)\) determine the possibility of using the \(j\)-th control method. The cluster checks the value of the parameter \(f_j\) in the tolerance field \([\varepsilon_j^{\text{min}}, \varepsilon_j^{\text{max}}]\):

\[
\varepsilon_j^{\text{min}} < f_j(x_1(t), x_2(t), \ldots, x_n(t)) < \varepsilon_j^{\text{max}}.
\]

If the object is operable by the checked parameter, then the value of the parameter \(r_i(t) = f_j(x_1, x_2, \ldots, x_n, t)\) and the logical signal \(q_i(t) = 1\) are transmitted to the CCD output. Otherwise, the functional output is blocked, and the signal \(q_i(t) = 0\) is applied to the logic output.

The value of the parameter \(r_i(t)\) can be used to further process of the monitoring object state, and the logical signal \(q_i\) to notify the network about the operability of the monitoring object.

Figure 2. Network structure of the FAS functional control

Figure 2 shows the structure of the FCN ED. Several FAC are connected to each FAS, which set the diagnostic mode depending on the parameters coming from the sensors.

The network simultaneously activates all FCN for which the necessary and sufficient conditions are met. The choice of the active FCN in the \(i\)-th cluster is determined by the logic of cluster interaction, the internal logic of the cluster, and the values of the parameters coming from the sensors. As a result of selecting the control mode, the signal \(r_{ij}(x_1, x_2, \ldots, x_n, t)\) is supplied to the network, and the logic diagnostic signal of the fault diagnosis \(q_i(t)\) is output to the EDC. The rate of change of the distributed FCN states is about one megahertz throughout the network.

5. Conclusion
Distributed FCN based on CCD have a speed of about one megahertz. The signal processing speed is determined in the CCD by key schemes in the analog logic circuits (speed of about
a hundred nanoseconds), analog methods of calculating function values, accelerated traffic for transmitting diagnostic information between interacting FAS process control.

The speed of the SFC based on the CCD allows one to embed a knowledge processing system in the complex of operational control of the parameters of the ED. The unification of signals in a distributed EDCS allows combining CCD into clusters for processing modes of controlling the characteristics of FAS complex EDs.

References

[1] GOST 26656-85 Technical diagnostics. Controllability. General requirements (Moscow: Standards Publishers)
[2] GOST 20911-89 1985 Technical diagnostics. Terms and Definitions. (Moscow: Standards Publishers)
[3] Davydov N 1988 Technical diagnostics of electronic devices and systems (Moscow:: Radio and communications)
[4] Safonov V 2005 Expert systems 2005 Intellectual assistants to specialists (St. Petersburg: St. Petersburg organization of the society “Knowledge” publishers)
[5] Jackson D 2001 Introduction to Expert Systems (Moscow: I.D. Williams Publishers)
[6] Jarratano D and Riley G 2007 Expert systems: principles of development and programming (Moscow:: I.D. Williams Publishers)
[7] Vorob'ev A and Lagoiko S 2015 Software systems and computational methods 4 437 DOI: 10.7256/2305-6061.2014.4.13995
[8] Dembitsky N 2018 J. Aerospace Instrum. 28
[9] Bratt A and Macbeth I 1998 DPAD2 17 67
[10] Kozlovaand T, Ignatiev A and Samoilova E 2011 Bulletin of the Saratov State Tech. Univ. 2 219
[11] Koptelova I and Silkin I 2011 Bulletin of the Saratov State Tech. Univ. 2 104
[12] Mazepa R and Kirzhakov V 2005 Inform. Technol. in design and prod. 2 13
[13] Palyukh B, Kakatunova T, Dli M and Baguzova O 2013 Program. Prod. Syst. 4 30
[14] Moreno C and Espejo E 2015 Engin. Failure Analys. 53 24
[15] Liberado E and et al 2015 Expert Systems with Applic. 3562