Dynamic theory of information – the basis for real time systems

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Динамічна теорія інформації – основа систем реального часу

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***Abstract*—Peculiarities of computing in real time systems are considered in the report. It is revealed, that traditional principles of an analog-to-digital conversion (sampling, quantization and encoding), which have been developed for systems, oriented on transferring and registration of information, don't meet requirements of real time systems with a feedback. The same thing concerns to principles of computing process organization. The new theoretical fundamentals and principles of information reconciliation of means for information conversion and processing are proposed for real time systems. They are based on a system approach and take into account peculiarities of real time systems, their requirements and restrictions, solvable tasks, and allow to evaluate the signal dynamics, information and precision characteristics of methods of a continuous signal digital presentation, and to select the most effective method for a certain case.**

***Анотація*—В доповіді розглядаються особливості роботи обчислювальних засобів в системах реального часу. Показано, що традиційні основи аналого-цифрового перетворення сигналів (дискретизація, квантування та кодування), які розроблялись для систем передачі і реєстрації інформації, не відповідають умовам систем реального часу із зворотним зв'язком. Це ж стосується і принципів організації обчислювального процесу. Пропонуються нові теоретичні основи і принципи інформаційного узгодження засобів перетворення і обробки інформації в системах реального часу, які базуються на системному підході, враховують особливості систем реального часу, їх вимоги та обмеження, розв'язувані задачі і дозволяють оцінити динаміку сигналів, інформаційні і точністні характеристики методів цифрового подання неперервних сигналів та вибрати з них найбільш ефективний для даного випадку.**

***Keywords*—real time system, analog-to-digital conversion, system approach, dynamic information, δ-entropy.**

***Ключові слова*—системи реального часу, аналого-цифрове перетворення, системний підхід, динамічна інформація, δ-ентропія.**

I. INTRODUCTION

Computing in real time systems with fast processes (automated control systems of moving objects, technological processes, and digital-to-analog modeling complexes and so on) has a number of peculiarities which result from a necessity to converse form of information presentation, and to provide requirements of real time.

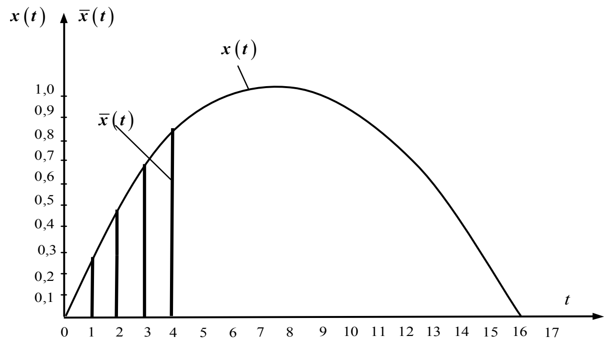
Systems with a feedback are the most complex real time systems, because besides providing productivity, information processing efficiency is required in order to reduce a delay of information in a feedback contour.

II. STATE OF PROBLEM

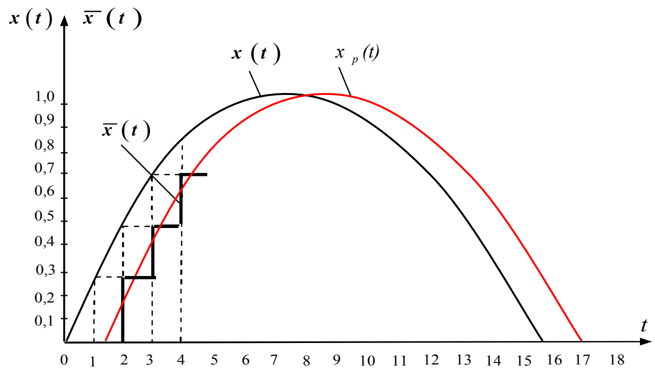
The traditional approach to analog-to-digital conversion consists in conversion of a continuous physical signal with a finite spectrum that is considered as a continuous random process, in a random sequence of real values, which characterize the state of a random process in fixed time instants. Under that, analog-to-digital conversion comes to consecutive execution of three processes: sampling, quantization and encoding. In the theory of analog-to-digital conversion there were developed some approaches, which allow to optimize each of these processes and to provide minimal number of signal samples, minimal number of quantization levels under given variance of quantization noise and minimal number of information bits in one sample. These theoretical fundamentals have been developed for systems of communications and storing of large arrays of information, which demand corresponding channels for transferring and memory capacity for storing. Indeed, optimization of system with respect to the criterion of information amount allows to relieve transferring channels, to lower requirements to these channels or to reduce their cost (to resolve the problems of communication), to reduce memory capacity (to resolve the problems of information storing). The high precision of a signal sample presentation provides principle possibility for further recovery of a signal form with a required precision. Conditionally such model can be named the measuring model.

Presence of information lag, caused by finite time of analog-to-digit conversion, transferring and storing, is not essential for registration systems. It should be reconciled only throughput of all tract elements. Information processing and restoration of a continuous signal form are accomplished separately, not in real time, by other means and therefore they are not taken into account while considering the process of an analog-to-digit conversion for registration and transfer of information. Time of processing and restoration of a continuous signal form are not fundamental for such systems. Information storing is accomplished for further processing not in real time and information processing substantially comes to computing characteristics of random processes: mathematical expectation, variance, correlation functions and matrices, coefficients of discrete Fourier transform. In this case, sampling of the process according to the Kotelnikov-Nyquist theorem or the correlation interval provides the required accuracy of characteristic computation of a random process with a minimal number of samples. However, sampling of the process with a long time step leads to necessity of considerable increasing of time interval, within the analysis of characteristics is being executed, and moreover, the restoration of a continuous signal form by Kotelnikov series causes considerable difficulties by using both analog and digital way of realization. Actually, the sampling for signal restoration is accomplished with considerably shorter time step than according to Kotelnikov theorem, and a restoration of a signal is executed by means of interpolating polynomials of a zero, the first or a higher order. Hereby, the peculiarity of interpolating methods is the principle necessity of introducing a delay during signal restoration that restricts their usage in real time systems of closed loop types. Extrapolating methods, which are used to except a delay, lead to greater error of signal restoration that grows with increasing of a sampling increment.

Curves of an analog-to-digital conversion are given in fig.1: a) ideal conversion without delay; б) real conversion with delay (1 clock cycle for an analog-to-digital conversion and 0,5 of a clock cycle at the expense of stairstepping of approximation).



a) Ideal conversion without delay



b) Real conversion with delay

Fig. 1. Curves of an analog-to-digital conversion

In addition, practically they are not acceptable for direct processing of values of signal samples, which have been obtained with methods of optimal or economical quantization in accordance with a likelihood of signal values.

Thus, the classical model of analog-to-digital conversion, which provides a minimum of information, transmitted and stored in registration systems, does not take into account particularities of subsequent processing and restoration of a continuous signal form and does not provide the overall system optimization even not in real time. At the same time, the traditional Neumann organization of computational process, that ensures minimization of the cost of computing tools, has not sufficient possibilities to increase their productivity and, in addition, does not take into account particularities of control systems and does not provide high requirements to operability of information processing. It concerns to organization problem of operational information input-output, memory organization, information processing and so on.

Thus, analysis of the state of problem shows:

- significant insufficiency of traditional fundamentals for conversion and processing information in control system with feedback;
- inconsistency of ways of digital presentation of a continuous signals with the tasks in control systems, methods of analog-to-digital conversion and forms of information presentation at the ADC output with the ways of the information processing;
- mismatch of organization principles of computing in universal computers, complexes and systems to control system requirements for information processing speed.

III. STATEMENT OF PROBLEM

As follows from the above there is a necessity of system approach to issues of conversion, processing and recovery of a continuous form of a signal.

The goal of this research is to create theoretical fundamentals and development of principles of information coordination tools for conversion and processing in real time systems, as well as principles of computing organization in control systems for fast and complex processes.

IV. DYNAMIC THEORY OF INFORMATION - THE BASIS FOR REAL TIME SYSTEMS

To evaluate quality of information systems it's widely used theoretical and informative presentations, which constitute substantial essence uncertainty, suddenness, diversity. Information is a map of this diversity. In each case, there are many forms (modes) of diversity, which is determined by specific conditions, requirements, limitations, etc. That's why any definition of information associated with a particular model of reality, that is underlie a study and which determines the diversity which system quality or criterion of its efficiency depends more from. Choice of information measure cannot be settled by means of mathematics, and is purely heuristic procedure that should take into account specific conditions, requirements and peculiarities.

In order to select information measure, requirements for digital presentation of continuous signals, let us consider problems and particularities of real time systems from the side of next following devices and restoration of a continuous signal form as well as criteria of evaluation of presentation quality.

Signals of real world have often continuous character and map object behavior or processes, which take place on the object. In real time systems information about the signal value are extracted traditionally in sampling instants, from which signal behavior can be restored if there are certain selection of signal sampling increment and the appropriate approximation method. In addition, information about signal variations within time interval or signal behavior can be extracted from the signal.

Each type of information has its own way of digital presentation of a continuous signal. There is a relationship between these types of information, so in case of carrying out the relevant conditions, transitions from one type of information to another are possible. Information about the behavior of the signal are the most complete information about it, thus it can be easy obtained information about the value of the signal at fixed moments of time or about variations of the signal at a time span. There is a relationship between these types of information, so in case of carrying out the relevant conditions it is possible transitions from one type of information to another. Transition from information about the signal value to information about to its behavior is more complicated.

Considered kinds of information show different characteristics of a signal, therefore their use is defined by the character of problems, which are resolved by an information control system.

Conducted studies have shown the following:

- codes of samples should save inside themselves the parameter value to provide the possibility to process and restore a continuous signal form in real time;
- the main sources of errors of digital presentation of a continuous signal are information delay in feedback contour, which is determined by latency of analog-to-digital conversion, and signal approximation on discrete samples;
- the problem of delay reduction comes to cutting down of information content in one sample under minimally possible sampling increment within technical conditions, unlike conventional approach of cutting down of information content by reducing sample number;
- the concept and the measure of information and system error change in dependance of concrete conditions, demands and limitations due to the models of considered processes. In case of need to process values of random quantity, which characterize physical parameters of system, their uncertainty should be considered in terms of uncertainty of physical parameter value, since time and complexity of value processing directly depend on digital capacity of value presentation. In case of need to restore the continuous signal form in close control contour, which maps behavior of physical system, uncertainty should be considered as uncertainty of parameter variation, since main errors, in these conditions, result from digital presentation of a continuous signal and delay, which are defined by process sampling increment. In order to reduce sampling increment it should cut down redundant information and process only useful information which are in process changes, that is in its dynamics.

The value (quantity) of the physical parameter, presented in reference units (quanta), which characterize the precision of its presentation, has been chosen as the main characteristic of physical parameter, which is operated in the computing engineering, and logarithm of quantization level number of this quantity has been chosen as information measure of parameter of this quantity, and this logarithm is one greater than the parameter value in quanta.

Unlike the Shannon entropy concept of the random quantity state, the entropy concept of value of a random quantity, that represents average number of bits, fallen on one value of random quantity, has been introduced. The introduced concept of adjusted entropy of random quantity characterizes dispersion over digit capacity for random value presentation and allows to evaluate reasonability to use variable digit capacity for presentation of array numbers.

It has been introduced the concept of the *δ*-entropy, that presents average value of the modulus of the random process derivative and characterizes the uncertainty of the random process changes, that is process dynamics. The concept of adjusted *δ*-entropy is defined by the distribution low for the signal derivatives and allows to compare according to dynamics processes of different nature, to evaluate their information content with different distribution laws for signal derivatives.

The reviewed methods for determination of mathematical expectation of random process derivative modulus, that is the basis of *δ*-entropy evaluation, for different methods of presentation of realisation or ansamble of realisation (in analytical form or grafically), for different methods of presentation of generalized characteristics of Gaussian processes (through given distribution law for derivative values, through given parameters of stationary normal process and its correlational function, through given power spectral density of stationary normal process) are considered.

The approaches to experimental measurement of *δ*-entropy over the random processes realisations are developed.

On basis of *δ*-entropy and adjusted *δ*-entropy it was received series of relations for evaluation of process dynamics and informational content of process, necessary number of samples for process presentation, sampling increment, errors and amount of information that are obtained under sampling with constant or variable increment, under quantization by constant or variable increments. Relations for estimating of benefits or losses during sampling and quantization with variable or constant step and quantum are received.

The choosen information measure allows to evaluate not only the amount of useful (dynamic) information, but also system error, which is brought by the feedback contour.

Thereby, the concept and considered issues, introduced in this work, are the framework of dynamic theory of information. The dynamis theory of information is based on system approach, takes into account particularities of real time systems, their requirements and limitations, resolved problems, and allows to evaluate the signal dynamics, informational and precisional characteristics of methods for digital presentation of continuous signals, and to select from them the most effective method for given case [1].

The block diagram of the algorithm for analog-incremental conversion on base of presented approaches is given in fig.2, in fig.3 – the diagram of the analog-incremental conversion with signal extrapolation during conversion and information processing in a feedback contour.

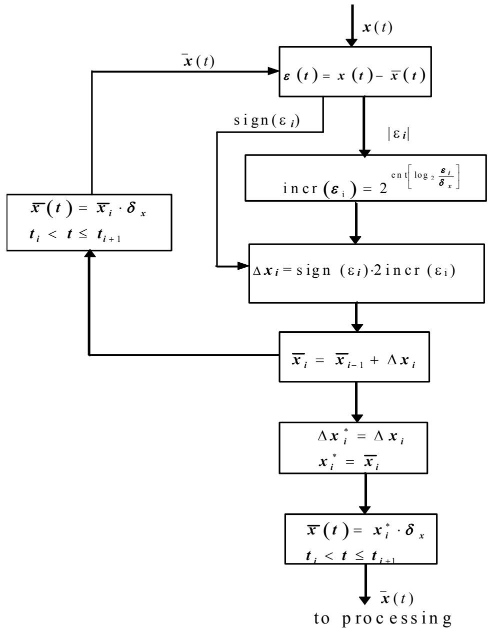


Fig. 2. The block diagram of the algorithm for analog-incremental conversion

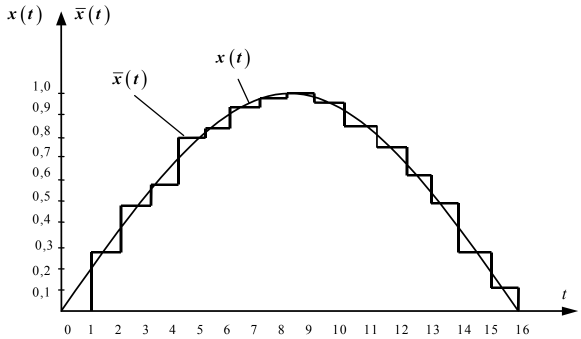


Fig. 3. The diagram of the analog-incremental conversion

The variant of analog-incremental conversion realisation is given in fig.4.

Here the subtractor (SUB) determines difference between the input signal and the feedback signal from DAC, which is compared with the row of treshhold elements (TE), weights of which are multiple of degree of two. The logical circuit (LC) extracts the most significant from treshhold elements, that was actuated from the difference signal. The encoder (Enc) codes number of this treshhold element and yields encoded value of difference (increment) to the output. The adder accumulator (AA) sums up subject to sign of difference to form a feedback signal through DAC. The complete digital value of a signal can be also took off the AA, but that value is not always used.

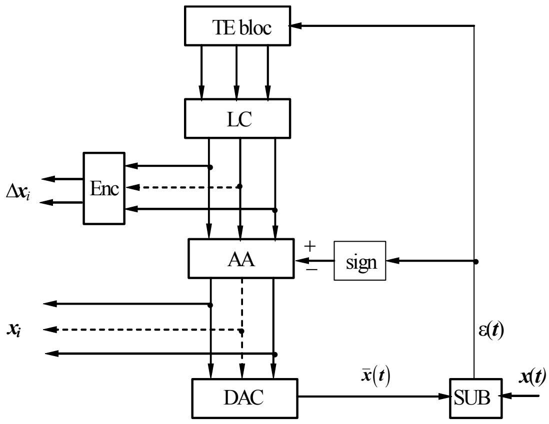


Fig. 4. The block diagram of the analog-incremental converter

The recurrent algorithms and the circuits of signal digital scaling and signal squaring are given in fig.5 and 6, respectively. Operations are executed without multiplication operation, scaling during one clock cycle, and squaring during two clock cycles.

The scaling operation:

$$y = k \cdot x_i, \qquad y_{i+1} = k \cdot x_{i+1},$$

$$x_{i+1} = x_i + \Delta x_i,$$

$$y_{i+1} = kx_i + k\Delta x_i = y_i + k\Delta x_i,$$

Since increments $\Delta x = \left(2^j\right)$, then $y_{i+1} = y_i \pm k2^j$.

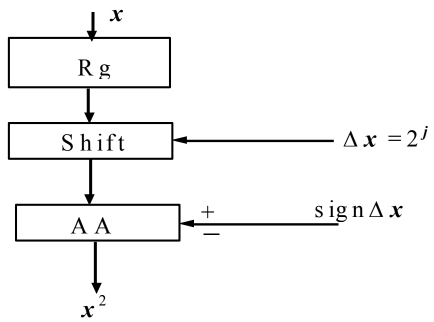


Fig. 5. The circuits of signal digital scaling

The squaring operation:

$$y_i = x_i^2, \qquad y_{i+1} = x_{i+1}^2;$$

$$x_{i+1} = x_i \pm \Delta x_i;$$

$$y_{i+1} = x_i^2 \pm x_i \Delta x \pm x_{i+1} \Delta x_i = y \pm x_i \Delta x_i \pm x_{i+1} \Delta x_i.$$

$$y_{i+1} = y_i \pm 2^j x_i \pm 2^j x_{i+1}.$$

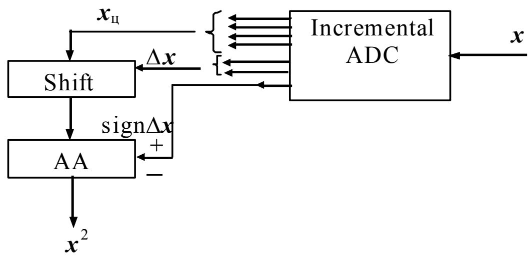


Fig. 6. The circuits of digital signal squaring

The examples of use of developed information basis for technical realisation for signal involution into other degrees, including fractional, for calculation of functions, polynomials, correlational functions, coefficients of discrete Fourier transform, digital filtration and so on, are also given in this report.

This realisation is especially effective in modes of function generation and signal (argument) tracking, that takes place practically in all tasks of information processing and in real time control.

All calculations in all these tasks are executed without a multiplication operation, which is substituted for shift operation on an arbitrary number of bits and which is executed during one clock cycle with considerably less hardware costs. Further development of the dynamic theory of information was directed on resolving of systems of linear algebraic, integral and differential equations with partial derivatives and so on, and also on intelligent perception and preliminary image processing in real time systems. More than 200 patents on inventions have been got, many of them have been implemented in real time processors, complexes and systems.

CONCLUSIONS

The fundamental framework of the work is the system approach to processes totality of analog-to-digital conversion, a continuous signal form processing and restoration, to computing process organization, which subordinates them to unitary quality criterion and makes corresponding requirements to realization of each process in a complex. Taking into account peculiarities of real time systems it allow in information way to tradeoff methods of digital presentation of continuous signals, analog-to-digital conversion algorithms, which correspond to these methods, information processing methods, which take into account methods of digital presentation of continuous signals and form of information at an ADC output for cases with one and many channels, principles of computing process organization in dedicated and task-oriented processors and systems.

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