HARDWARE AND SOFTWARE SYSTEM FOR RECORDING BIOPREPARATION PRODUCTION PROCESS PARAMETERS

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Abstract. The article describes the development of a hardware and software system to provide researchers and technologists with information on industrial fermentation processes. The hardware and software system is essentially an information subsystem for measuring the parameters of the culture growth environment, accumulating information over a specific cultivation cycle, and processing current values of the fermentation environment parameters during the stages of culture growth, storage, and death. One of the challenges encountered in organizing the industrial production of microbiological plant protection products (hereinafter referred to as MBPPs) is the lack of specialized, mass-produced fermentation equipment and hardware and software support for the technological processes. Laboratory equipment with a wide range of applications is used for research purposes, while for production preference is given to Software and Hardware Complex (SHC) based on industrial controllers, which are often integrated into and designed specifically for use with expensive laboratory equipment. The FU-500 fermentation unit, which produces a batch culture, served as the subject of the study. SHC, based on an Arduino controller, allows for real-time acquisition of process parameters, displaying them on an indicator, and recording them to a memory card for further processing on a personal computer. Using the SHC to study the biopharmaceutical production process on the FU-500 unit allows for the acquisition of experimental dynamic characteristics via control and disturbance channels; approximation of experimental dynamic characteristics using transfer characteristics; development of a regression model for the fermentation process quality for a specific biopharmaceutical produced on the unit; and development of a strategy for synthesizing an automated process control system for biopharmaceutical production.

Keywords: fermentation, automation, data collection, hardware, software.

Introduction

Modern requirements for the study of fermentation processes include the availability of systems for real-time data acquisition and processing to enable effective monitoring and control of fermentation [1; 2].

Instrumentation of fermentation systems makes it possible to obtain experimental data for developing mathematical models (e.g., regression models), analysing the growth and production of biological products, and predicting optimal technological regimes with higher accuracy and reduced time [3; 4].

The entire dataset obtained by instrumental methods can be conventionally divided into two main groups: I – physical and physicochemical parameters; II – physicobiochemical parameters.

Existing automated fermentation control systems typically monitor the following parameters: temperature, pressure, dissolved oxygen concentration, redox potential, airflow rate, agitator speed, liquid level, and foam formation [2]. In addition, these systems perform dosing of technological fluids.

In recent years, significant progress has been achieved in the development of digital and IoT-based systems for bioprocess monitoring. For example, [1] and [2] investigated the use of biosensors for real-time monitoring in biomanufacturing environments, [3] demonstrated the application of Industrial IoT technologies for improving data acquisition and process transparency in bioprocess industries.

At the same time, modern approaches such as digital twins and machine learning-based models [3-5] focus primarily on high-level data analysis and optimization, often relying on expensive and complex instrumentation.

One of the key challenges in organizing industrial production of microbiological plant protection products (MPPs) is the lack of specialized, mass-produced fermentation equipment. A similar limitation

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exists in the field of software and hardware support for such production systems, particularly with respect to dedicated research-oriented software and hardware complexes (SHC) [5; 6].

Therefore, the aim of this work is to develop a low-cost, scalable hardware and software system for real-time acquisition and processing of fermentation parameters, enabling experimental identification and modelling of the bioprocess.

Materials and methods

Fermenters are specialized equipment used for microbial fermentation, designed to ensure optimal conditions for achieving high efficiency and productivity. They provide controlled environments in which microorganisms, such as yeast and bacteria, convert substrates into valuable biochemical products. Due to this specialization, fermenters are widely used in industries such as food and beverage production and manufacturing of microbiological plant protection products, where fermentation plays a key role [1-3].

The identification and analysis of fermentation systems [1-4; 6] are performed to develop scientifically grounded research tools for evaluating both quantitative and qualitative characteristics of the final biological product, as well as for designing information and control systems for specific fermentation processes.

For such technological systems, batch (periodic) cultivation is typically employed, where microorganisms are grown in a closed system and the process proceeds in a cyclic manner. A simple batch culture with a limited initial amount of nutrient substrate represents a classical example of such a system. In closed systems, the biomass growth rate eventually approaches zero due either to substrate depletion or to the inhibitory effects of accumulated metabolic products [4].

Fundamental studies on the cultivation of microorganisms and cells, as presented in [7], remain relevant for modern biotechnological applications.

An analysis of the literature on monitoring and controlling fermentation parameters in the production of microbiological plant protection products was conducted. Based on this analysis, a parametric model of a typical fermentation system was developed. The FU-500 fermentation unit, developed by ETI "Biotekhnika" of NAAS, was selected as a representative object of study. The system includes: two FT-0.315 fermenters, one sterilizer, three units for water preparation, air sterilization, and exhaust filtration, and a centralized control panel.

A parametric diagram of a single fermenter, representing the complete set of its operational parameters and typical for most stirred-tank bioreactors, is shown in Fig. 1.

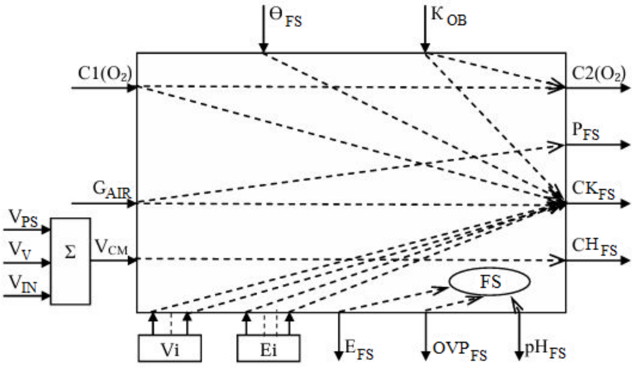

Fig. 1. **Parametric diagram of a fermenter**: V_{PS}, V_V, V_{IN} – nutrient medium, water and inoculum volumes respectively; V_i – additive components volume; G_{AIR} – air flow rate for fermentation substrate (FS) aeration; $C_1(O_2)$, $C_2(O_2)$ – oxygen concentration in inlet and outlet air respectively; Θ_{FS} – FS temperature; K_{OB} – FS mixing coefficient; CH_{FS}, CK_{FS} – the initial and final titer of biological product (target microorganism concentration); P_{FS} – surplus pressure in the fermenter; E_{FS}, OVP_{FS}, pH_{FS} – FS electrical conductivity, redox potential, pH; E_i – other FS affecting factors

In this system, the main indicator of the completion of the fermentation process is the parameter CK_{FS} (titer of the final biological product). Its value during the process is determined by sampling intermediate fermentation broth (*FS*) followed by measurement using appropriate analytical methods [1; 8].

Similarly, the parameters CH_{FS}, V_{PS}, V_B, and V_{IN}, as well as their ratios, are determined individually during the process. These parameters, along with their quantitative values and the energy costs associated with sterilization of the entire system during filling of fermentation vessels with volumes of 125 L and 250 L, respectively, are classified as resource parameters in the evaluation of economic efficiency [2; 4]. This category also includes electricity consumption throughout the fermentation process.

All other parameters are considered technological (input and output) variables that influence process efficiency, including key indicators such as *CK* and *FS*.

It should be noted that parameters such as E_{FS}, OVP_{FS}, and pH_{FS}, as well as their dynamic and steady-state characteristics, determine the state of the fermentation medium throughout the entire production cycle of the biological product [2; 8; 9]. Electrophysical influence channels (E_i) can be used as control inputs affecting these parameters.

To automate the study of the biological production process, a Software and Hardware Complex (SHC) was developed. The general view of the structural and functional diagram and experimental model of the SHC is given in Fig. 2.

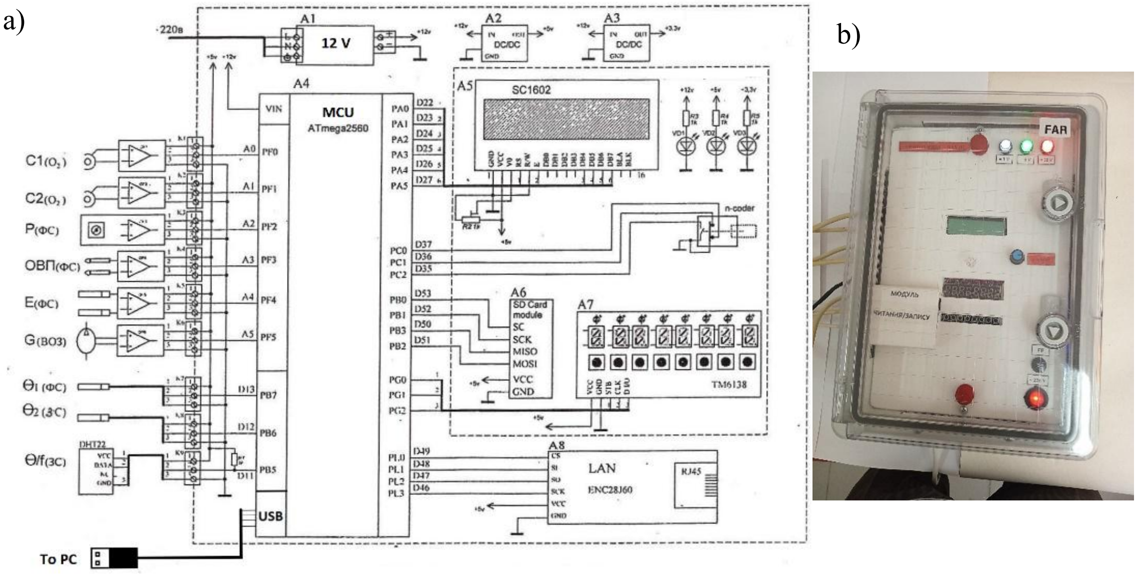

Fig. 2. **General view of the structural and functional diagram (a) and experimental model (b) of the Software and Hardware Complex (SHC)**

The SHC is based on the ATmega2560-16AU microcontroller and includes the following components:

- sensors for converting physical quantities into electrical signals (analog or digital) [10; 11];
- sensor interface (adapter) module;
- operator console (display and keyboard) for data visualization and control;
- LAN interface module for communication with a computer [4];
- power supply units.

The hardware implementation of the SHC based on the Arduino Mega2560 board with the ATmega2560 microcontroller determined the feasibility of choosing the Arduino platform in terms of software development; for this Arduino platform, there is a sufficient number of materials [7; 9; 12; 13] for development, starting with libraries that can be used to simplify programming in *C/C++*.

The software performs polling of digital and analog sensors of technological process parameters, carries out their mathematical processing, storage and display on indicators. It has the ability to transfer the processed data for storage on an SD memory card or for further processing on a personal computer (Fig. 3).

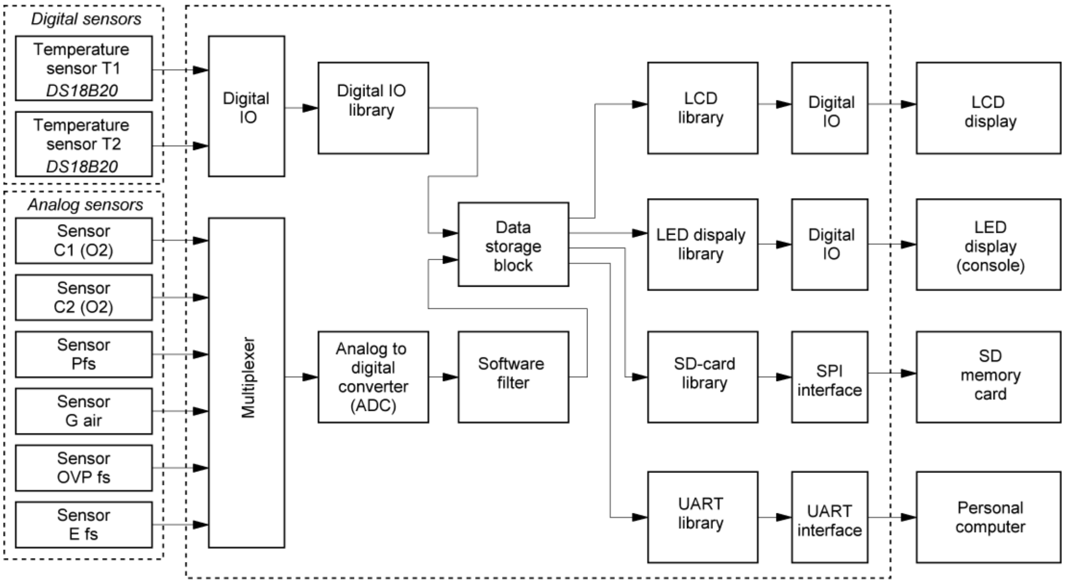

Fig. 3. **Software structure**

The system uses both digital and analog sensors to acquire process parameters. Digital temperature sensors of the DS18B20 type are employed, which are compact devices with a measurement range of −55 to + 125 °C and an accuracy of ± .1 °C. They communicate via a 1-wire interface, requiring only a single connection to the microcontroller input-output ports, and are accessed through a dedicated software library. These sensors are pre-calibrated and provide direct temperature readings, eliminating the need for further filtering or conversion [1; 7].

Analog sensors provide a voltage output in the range of 0–5 V. The built-in 10-bit, 8-channel analog-to-digital converter (ADC) of the ATmega2560 microcontroller converts these signals into digital values ranging from 0 to 1023. Since only one ADC is available, signals are sampled sequentially through a multiplexer. To reduce measurement noise caused by electromagnetic interference, supply voltage fluctuations, or other factors, the signals are filtered using a digital averaging filter [1; 8].

After filtering, the digital values are converted from raw ADC units into corresponding technological units, enabling meaningful interpretation of the measurements. All processed data are stored in the microcontroller’s RAM, with each memory cell allocated to a specific measured parameter. This stored information can subsequently be accessed by other software modules for further analysis and control [4; 6].

To visualize the measurements in real time, the system uses an SC1602 alphanumeric liquid crystal display. The display consists of two lines of 16 characters: the first line shows the parameter name, while the second line indicates its current value. Parameters are updated cyclically at intervals of 1 s using a dedicated display control library [1].

For long-term data storage and transfer, an SD memory card is integrated via the SPI interface. Data are recorded in tabular form with time stamps, typically at 1 s intervals, which can be modified as required. Additionally, the system provides real-time data transmission to a personal computer via the UART interface for further processing, including plotting dynamic graphs or saving data in tabular form. Data are transmitted in packets, with a default interval of 1 s, configurable during system setup [4**;** 7].

Results and discussion

Culture in closed systems (as a simple periodic one) is always in a transitional state in which the process rate tends to zero. The duration of growth limited by the substrate can be increased by adding a substrate. Such a culture is called a periodic culture with the addition of food sources.

The proposed information support for the analysis of fermentation processes in closed systems is based on the data of scientific works on factor influence, the results of theoretical substantiation of the structures of control complexes for the fermentation process, as well as the development of industrial microprocessor systems for controlling the processes of closed and open systems.

The plan for experimental research of the fermentation process on the FU-500 unit (using SHC) along the channels, $\Theta_{FS} \rightarrow CK_{FS}$; $C1(O_2)$, $C2(O_2) \rightarrow CK_{FS}$; $G_{AIR} \rightarrow P_{FS}$; $G_{AIR} \rightarrow CK_{FS}$ in the mode of continuous measurement and accumulation of information on the parameters of the FS state is reduced to performing a multifactorial experiment. Experiments are conducted at $V_{CM} \rightarrow$ const.

At the first stage, the purpose of experimental research is to determine the transfer functions of the control channels, perturbations and fixation of the parameters of E_{FS}, OVP_{FS}, pH_{FS}. The result is to obtain optimal values of the parameters that provide max CK_{FS}: $\Delta C(O_2) = C1(O_2) - C2(O_2)$; Θ_{FS}; K_{OB}; P_{FS}; CH_{FS} according to the existing control system. At the second stage, a search is made for methods and techniques for the parameters of the FS state, that is, the inclusion of new channels of influence in the structure of the control system.

The structural diagram of the fermenter as a control object obtained as a result of the experiments is shown in Fig. 4.

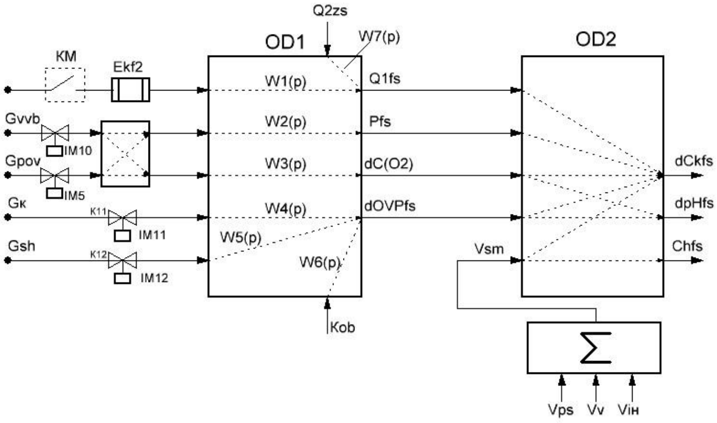

Fig. 4. **Structural diagram of the fermenter as a control object:** $W_i(p)$ – transfer functions of OD_1 through the channels of influencing parameters; G_{air} – air flow rate discharged from the fermenter; G_{pov} – air flow rate supplied to the fermenter; G_k – acid flow rate; G_{sh} – alkali flow rate; KM – power switch for supplying energy to the electric heater E_Kf_2; IM_{10}, IM_5, IM_{11}, IM_{12} – electromotive actuators of solenoid valves K_{10}, K_5, K_{11}, K_{12}; K_{ob} – mixing coefficient for FS

Experimental validation of the system was carried out on the FU-500 fermentation unit. The system successfully recorded temperature and dissolved oxygen dynamics during the batch cultivation cycle. The obtained data demonstrated stable operation of the acquisition system and confirmed its suitability for further experimental studies.

The intermediate goal of the study is the synthesis of 4-channel regulation channels with optimal accuracy of ADC, which significantly facilitates the solution of the main task of managing the quality of bioproducts, as well as the development of a quality model of a biological preparation for periodic cultures. When determining static characteristics by the method of active experiment, increments of one of the input values are set at intervals of time Δt (while the other input values are constant). The fixation time is chosen from the condition.

$$\Delta t \geq (1.5 \div 2) T_p, \tag{1}$$

where T_p – maximum duration of the transient process in each value is sequentially changed from the minimum to the maximum value. In this case, the changes in the output value are regulated at each interval Δt.

A similar series of experiments for the same output value is carried out when changing another input. Then the static characteristics of OD_1 should have the following dependencies:

$$\Theta_{FS} = f(\%hro(E_k f_2)), \tag{2}$$

$$P_{FS} = f(G_{air}), \tag{3}$$

$$C(O_2) = f(G_{air}, K_{OB}), \tag{4}$$

$$OVP_{FS} = f\left(G_k, G_{sh}\right), \tag{5}$$

where %*hro* – percentage of the stroke of the regulating body;
$E_K f_2$ – electric heater of the fermenter;
P_{FS} – pressure in the fermenter;
Θ_{FS} – temperature of the fermentation substrate;
G_{AIR} – air flow rate;
$C(O_2)$– dissolved oxygen concentration;
K_{ob} – mixing coefficient;
OVP_{FS} – redox potential of the fermentation substrate;
G_k, *Gsh* – acid and alkali flow rate.

Transfer functions $W_1(p) – W_7(p)$ after processing experimental acceleration curves, their approximation taking into account equation (1), provide the basis for parametric, or structural synthesis of ADC. Already at the planning stage of a multifactor experiment, it is advisable to determine in advance for all 4 control circuits the structure of the control system control laws (any of them) and perform the experiments described above.

The final stage of the research (experimental) is reduced to removing the static and dynamic characteristics of $OD = (OD_1 + OD_2)$. The equations (2-5) could be written in the form:

$$CK_{FS} = f\left(\%hro\left(E_k f_2\right)\right); P_{FS}, C\left(O_2\right), OVP_{FS} \to \text{const}\,, \tag{6}$$

$$CK_{FS} = f\left(\%hro\left(K_{10}\right)\right); \Theta_{FS}, C\left(O_2\right), OVP_{FS} \to \text{const}\,, \tag{7}$$

$$CK_{FS} = f\left(\%hro\left(K_5\right)\right); \Theta_{FS}, P_{FS}, OVP_{FS} \to \text{const}\,, \tag{8}$$

$$CK_{FS} = f\left(\%hro\left(K_{11}\right)\right); \Theta_{FS}, P_{FS}, C\left(O_2\right) \to \text{const}\,, \tag{9}$$

$$CK_{FS} = f\left(\%hro\left(K_{12}\right)\right); \Theta_{FS}, P_{FS}, C\left(O_2\right) \to \text{const}\,, \tag{10}$$

where CK_{FS} is the static characteristics of the fermentation process, representing the dependence of output parameters on selected control inputs under steady-state conditions, i.e. quality indicator of the final biological product.

To assess the linearity of ADC, it may be sufficient to obtain static characteristics of *OD* of the form (6-10) (with one input and one output). The usefulness of the experiment in this case is to assess the sensitivity of the indicator CK_{FS} to the control effects of the parameters of the 4 channels of the ADC. This determines the ranking of the parameters (by the value of the coefficient of transfer of static characteristics), determines the limits of measurements of the control effects, determines the presence of optima (parabola), and subsequently the structure of the regression model of the quality of the biological product according to the dependence:

$$CK_{FS} = f\left(\Theta_{FS}, C\left(O_2\right), OVP_{FS}\right). \tag{11}$$

This relationship makes it possible to quantify the contribution of each control parameter to the resulting quality indicator. Based on the obtained coefficients, the most influential factors can be identified and prioritized for further optimization. In addition, the established model serves as a basis for selecting rational operating modes of the ADC and improving the overall efficiency of the biological product formation process.

The novelty of the proposed work lies in the following:

- development of a low-cost hardware-software system specifically adapted for experimental identification of fermentation processes;
- integration of multi-channel data acquisition with real-time processing and storage in a modular architecture based on an open platform;
- provision of experimental support for obtaining dynamic characteristics of the fermentation process via control and disturbance channels;
- enabling the synthesis of regression models and control strategies based on experimentally acquired data.

Conclusions

1. The developed hardware and software complex (SHC) provides multi-channel acquisition, processing, visualization, and storage of fermentation process parameters. The system has a modular and scalable architecture, allowing integration of additional sensors and functional modules. Experimental implementation confirmed stable operation with a measurement error of approximately ± 2% for analog channels and ± 0.6 °C for temperature measurements.
2. Due to its low cost, modular design, and scalability, the proposed system is suitable for laboratory research, educational applications, and long-term monitoring of technological processes, particularly in conditions with limited access to expensive industrial equipment.
3. Application of SHC on the FU-500 fermentation unit enables real-time acquisition of experimental data, including dynamic characteristics of the process along control and disturbance channels. The obtained data can be approximated using transfer functions and regression models, providing a basis for constructing semi-empirical models of the fermentation process and predicting its behavior under varying conditions.
4. The experimental data and derived models enable identification of key factors influencing the quality indicator CK_{FS} and provide a foundation for the synthesis of control strategies (including single-level and two-level systems), aimed at improving the efficiency and stability of biotechnological production processes.

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Author contributions

Conceptualization, D.K., A.R., V.D.; methodology, D.V. and M.S.; software; validation, A.R. and O.B.; formal analysis, O.B. and O.Z.; investigation, D.V. and M.S.; data curation, A.R., O.B. an O.Z.; writing – original draft preparation, D.V.; writing – review and editing, A.R., O.Z. and O.B.; visualization, V.D., M.S.; project administration, A.R.; funding acquisition, V.D. All authors have read and agreed to the published version of the manuscript.

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