

# Software implementation of a virtual laboratory bench for distance learning

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**Abstract.** The article discusses the functional development and integration into the educational process of a virtual laboratory stand, with the aim of digitalizing the educational processes of higher education without loss as educational services related to the completeness of mastering professional competencies in specialized engineering courses. The developed laboratory stand allows simulating technological processes implemented in an apparatus consisting of four connected tanks. Modeling such a complex technological process with many interconnected elements is necessary for the most detailed research and synthesis of automatic control systems for multiply connected objects. The program simulates two control loops, each of which can be switched to manual or automatic operation. To realize the maximum adequacy of the mathematical model, the program provides for the possibility of taking into account the influence of the actuators on the regulation process.

## 1 Introduction

The digital transformation of education is not just a necessary measure associated with the pandemic, but also a vector for the development of Russian education in the modern conditions of society. The use of digital technologies in the educational environment contributes to the introduction of inclusive learning, as well as the development of the mobility of educational processes. The main goal of digitalization of education is to effectively and flexibly apply the latest technologies to transition to a personalized and result-oriented educational process, which allows the implementation of distance education and online learning programs without losing the quality of educational services [1].

To achieve the goal of digital transformation of educational processes, it is necessary to solve the following tasks: the development of the material infrastructure of educational institutions, taking into account the introduction of new learning management systems, the development of digital educational and methodological materials and multimedia tools, which significantly increase the visibility of distance courses [2].

Information systems such as Zoom, Discord, Microsoft Teams, Skype, Moodle, etc. are widely used to implement lectures in distance learning. The listed information systems are quite well adapted for conducting theoretical studies, however, they do not allow carrying

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out full-fledged practical and laboratory work, which is characterized by the planning of an experiment, its implementation and processing of results, which are of particular relevance for training specialists in engineering [3].

In view of the above problems, the task of developing virtual laboratories is fundamental for the digital transformation of educational processes, in order to preserve the quality of educational services while personalizing education. Virtual stands for laboratory and practical work are aimed at the formation and development of key skills in working with modern measuring equipment, including performing measurements, processing and presenting measurement results, with an emphasis on automating all stages of working with measuring information, which allows you to most effectively implement the learning process in frontal or remote mode [4].

Virtual laboratories can be divided into several types:

- a virtual laboratory means a physically existing laboratory facility with the possibility of remote access, as well as the presence of measuring equipment that transmits the measurement results online to the user;
- a virtual laboratory is understood as a software-implemented mathematical model of a physically existing object, which can be located both on the server and on the user's computer, and which allows carrying out model experiments [5].

The main difficulty in the software implementation of a virtual laboratory is to ensure the adequacy of the mathematical model to a real physical process. Creation of a completely adequate mathematical model is practically impossible, the latter means that the virtual stand will always work under certain assumptions, describing only the basic processes. At the same time, given that it is they who are subject to study, the second type of virtual stands is the most promising for the organization of a distance educational process. At the same time, the development of the most adequate model is a task that must be pursued when developing a mathematical model of real processes [6].

Virtual stands have become widespread for the implementation of standard disciplines of the school curriculum, such as physics, chemistry, etc. However, laboratories that allow simulating the operation of technological installations, which are necessary for organizing work on specialized courses of higher education, such as "Theory of automatic control", "Automation of technological processes", etc., realizing professional competencies, are still quite rare. It should also be noted that they are characterized by a significant limitation of the implemented control laws, input actions, and also measured parameters [7].

The foregoing allows us to conclude about the relevance of the development of virtual laboratory stands for studying specialized courses.

Development of a virtual laboratory bench is impossible without a comprehensive understanding of the functioning of the process. This understanding usually manifests itself in the form of a mathematical model used to test the impact of various design decisions on the achievement of management objectives. When developing mathematical models of technological objects and processes, the developer needs to give answers to the following questions: how to choose the appropriate complexity of the model? how to describe model errors? how to linearize nonlinear models?

When creating a model, it is important to keep in mind that all real processes are complex, and, therefore, any attempt to construct an accurate description of an object is not feasible. Therefore, for the design of control (regulation) systems, it is advisable to have models that, on the one hand, reflect the features of the object that are important for design, but on the other hand, are not so complicated as to obscure the essence of the problem [8]. Building such a model is a non-trivial task that can be solved in several stages. As a rule, for the design of control systems, at the first stage, a simple model is developed, which is gradually supplemented and complicated in the process of developing the solution.

## 2 Experimental

Thus, the model should include a set of parameters of the main (important for control) features of the object, and also contains the minimum possible set of parameters of the main (important for control) features of the object.

The first possible approach to creating a model of an object is to build a certain structure of the model and use a so-called black box for modeling. With this approach, the parameters of the model are changed either empirically or on the basis of some algorithm until the dynamic behavior of the model and the object match well enough [9].

An alternative approach to the simulation problem is to use physical laws (such as conservation of mass, energy, and momentum) to build the model. This approach takes advantage of the fact that in any real system there are basic phenomenological laws that determine the relationship between all of its signals. In practice, the ideas of the black box and the phenomenological are combined to create a model. Phenomenological understanding is often key to understanding dynamics (including dominant parameters), nonlinearities, and significant temporal changes in a given system. This can help in the initial choice of model complexity. On the other hand, the black box approach often allows the selection of models for those parts of the object where the corresponding physics of the processes is so complex that it is difficult to find an appropriate phenomenological model [10].

Mathematical models of control objects can be presented in the form of differential or difference equations, as well as in the form of their combination. These models associate the inputs of an object with individual outputs and deal with a limited description of the system in the process of studying it.

Models in the form of differential equations.

These models represent an arbitrary order differential equation that directly connects the inputs of an object to its outputs [11]. These patterns are commonly referred to as entry-exit models. In the case of continuous time, these models take the form:

$$l\left(\frac{d^m y(t)}{dt^m}, \dots, y(t), \frac{d^{m-1} u(t)}{dt^{m-1}}, \dots, u(t)\right) = 0 \tag{1}$$

where  $l$  - is some, in the general case, nonlinear function,  $y(t)$  and  $u(t)$  are the output coordinate and the control action, respectively.

For linear systems, equation (2) takes the form of a transfer function:

$$\begin{aligned} a_m \frac{d^m y(t)}{dt^m} + a_{m-1} \frac{d^{m-1} y(t)}{dt^{m-1}} + \dots + a_1 \frac{dy(t)}{dt} + a_0 y(t) = \\ = b_n \frac{d^n u(t)}{dt^n} + b_{n-1} \frac{d^{n-1} u(t)}{dt^{n-1}} + \dots + b_1 \frac{du(t)}{dt} + b_0 u(t) \end{aligned} \tag{2}$$

Another powerful tool for representing I / O models is the transfer function. It is known that one of the most effective methods for studying linear differential equations is based on the Laplace transform, the most important of which is the replacement of differential equations by algebraic ones[12].

Applying the direct Laplace transform to equation (3) with zero initial conditions, we get:

$$\begin{aligned} a_m Y(S)S^m + a_{m-1} Y(S)S^{m-1} + \dots + a_1 Y(S)S + a_0 Y(S)S = \\ = b_n U(S)S^n + b_{n-1} U(S)S^{n-1} + \dots + b_1 U(S)S + b_0 U(S)S \end{aligned} \tag{3}$$

After simple mathematical transformations of equation (3), we obtain an expression that connects the image of the output signal  $Y(S)$  with the image of the input signal  $U(S)$ .

$$Y(S) = \frac{b_n S^n + b_{n-1} S^{n-1} + \dots + b_1 S + b_0}{a_m S^m + a_{m-1} S^{m-1} + \dots + a_1 S + a_0} U(S) = W(S)U(S) \tag{4}$$

where  $W(S)$  is the transfer function of the system (object) described by the equation (5).

Thus, the transfer function establishes an unambiguous connection between the input and output of the system (object) and can be used as its (his) model [13].

The state variable model is a system of differential equations. The meaning of such a representation of the mathematical model of an object is that, in addition to access to external variables (input and output coordinates), it reflects the internal variables of the object, the knowledge of which is necessary when designing control systems using modern theory [14].

$$W(S) = \frac{Y(S)}{U(S)} = \frac{b_{m-1} S^{m-1} + b_{m-2} S^{m-2} + \dots + b_1 S + b_0}{S^m + a_{m-1} S^{m-1} + \dots + a_1 S + a_0} = \frac{B(S)}{A(S)} \tag{5}$$

Consider a model of an object, given as a relative function, which we represent as:

$$W(S) = \frac{1}{A(S)} * B(S) = W_1(S)W_2(S) = \frac{X(S)}{U(S)} * \frac{Y(S)}{X(S)} \tag{6}$$

where

$$W_1(S) = \frac{X(S)}{U(S)} = \frac{1}{A(S)}, W_2(S) = \frac{Y(S)}{X(S)} = B(S), \quad X(S)$$

- intermediate variable .

The transfer function  $W_1(S)$  corresponds to the differential equation:

$$a_m \frac{d^m x(t)}{dt^m} + a_{m-1} \frac{d^{m-1} x(t)}{dt^{m-1}} + \dots + a_1 \frac{dx(t)}{dt} + a_0 x(t) = u(t) \tag{7}$$

By substitutions  $\frac{dx}{dt} = x_1, \frac{dx_1}{dt} = x_2, \dots, \frac{dx_{m-1}}{dt} = x_m$  imagine (7) in the form of a system of equations:

$$\left\{ \begin{array}{l} \frac{dx(t)}{dt} = x_1(t) \\ \frac{dx_1(t)}{dt} = x_2(t) \\ \vdots \\ \frac{dx_m(t)}{dt} = -a_{m-1}x_{m-1}(t) - \dots - a_0x(t) + u(t) \end{array} \right. \tag{8}$$

Introducing (8) in matrix form, we get:

$$x(t) = \begin{bmatrix} 0 & 1 & 0 & \dots & 0 \\ 0 & 0 & 1 & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \dots & 1 \\ -a_0 & -a_1 & -a_2 & \dots & -a_{m-1} \end{bmatrix} x(t) + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} u(t) \tag{9}$$

or

$$x(t) = Ax(t) + Bu(t)$$

where  $x(t)$ - is a column vector of state variables.

The differential equation corresponding to the transfer function  $W_2(S)$  can be written as:

$$y(t) = b_{m-1} \frac{d^{m-1}x(t)}{dt^{m-1}} + b_{m-2} \frac{d^{m-2}x(t)}{dt^{m-2}} + \dots + b_1 \frac{dx(t)}{dt} + b_0x(t) \quad (10)$$

Taking into account (8), we rewrite equation (10):

$$y(t) = b_{m-1}x_{m-1}(t) + b_{m-2}x_{m-2}(t) + \dots + b_1x_1(t) + b_0x(t) \quad (11)$$

In matrix form, expression (10) takes the form:

$$y(t) = [b_0 \quad b_1 \quad b_2 \dots b_{m-1}]x(t) = Cx(t) \quad (12)$$

Thus, the model presented in the form of transfer function (2), taking into account (11) and (12), can be represented in the form of state variables:

$$\begin{cases} \dot{x}(t) = Ax(t) + Bu(t) \\ y(t) = Cx(t) \end{cases}$$

### 3 Evaluation

This article discusses a virtual laboratory bench that allows you to simulate technological processes implemented in an apparatus consisting of four connected tanks. Modeling such a complex technological process with many interconnected elements is necessary for the most detailed research and synthesis of automatic control systems for multiply connected objects [15]. Let's consider in more detail the application interface - a virtual laboratory stand. The main application window looks like an interactive functional automation diagram. The functional diagram displays the dependencies of a multi-connected object consisting of four reservoirs (Fig. 1). Next, let's consider the functionality of the buttons and tabs of the application shown in Fig.1.

Using the "Start" button, it is possible to start or continue the application, while pressing the "Pause" button it is possible to pause the simulation process itself. Pressing the "Record" button will allow you to register the main technological parameters in a temporary file, such as the time, the angle of rotation of theme control valves and the water level in tanks 1 and 2. Activation of the "Save" button saves the recorded data to disk, and when you press the «Clear» the temporary file is cleared.

The "Regulation" panel is used to control the analog or digital simulation method.

To launch methodological instructions for laboratory work, the "Methodological instructions" button is intended, which launches the compiled task file [16].

The "Scope" window is intended for continuous monitoring of the liquid level in the tanks.

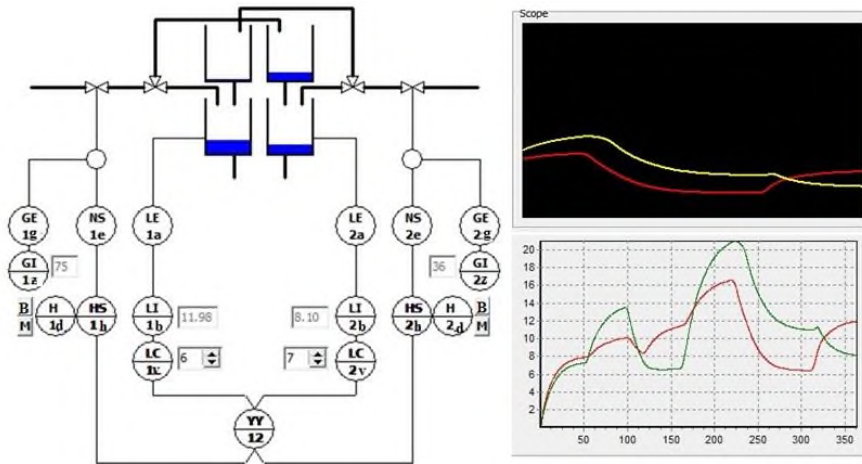
The "View measurement results" window will allow you to track the readings of changes in the water level in the tanks and the angles of rotation of the control valves recorded in the temporary file.

The choice of the dependencies of interest is carried out by activating the switches  $h_1(t)$ ,  $h_2(t)$ ,  $f_1(t)$  and  $f_2(t)$ , and their construction - by pressing the button "Build".

The program simulates two control loops, each of which can be switched to manual or automatic operation.

Let's consider a list of devices whose operation was simulated in the application for switching the operating mode of the primary circuit [17].

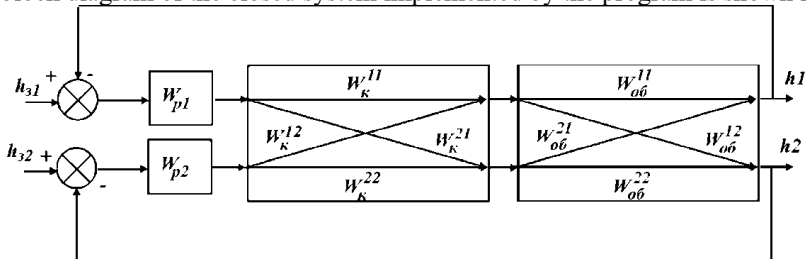
To account for the water level in the tanks, the operation of the LE-1a level sensor and the LI-1b device outputting the readings was simulated; to implement the possibility of regulating the water level in the tank, the functionality of the LC-1c level controller and YY-12 compensator was implemented. There is also an HS-1g operating mode switch, an NS-1e magnetic starter, an actuator for a B1 regulation valve. the HS-1g mode switch is used on the symbol of which you need to point the mouse pointer and press the left button. After switching the circuit to the manual control mode, next to the symbol of the H-1d push-button station, buttons "B" and "M" will appear, clicking on which you can control the opening angle of the control valve B1. Switching the operating mode of the second circuit (LE-2a level sensor showing LI-2b device, LC-2b level controller, YY-12 compensator, HS-2g operating mode switch, NS-2e magnetic starter, B2 control valve actuator) is carried out in the same way [18].



**Fig. 1.** The main application window.

To realize the maximum adequacy of the mathematical model, the program provides for the possibility of taking into account the influence of the actuators on the regulation process. To implement this feature, you need to move the mouse pointer over the symbol of the actuator and click on the left mouse button. This will lead to the appearance of the window, where it is necessary to activate the switch "Consider the influence of IM" and set the gear ratio  $K_{AM} = \frac{100}{T_{AM}}$ , where  $T_{AM}$  is the time of rotation of the actuator shaft by **100%**, and then press the Enter button.

The block diagram of the closed system implemented by the program is shown in Fig. 2.



**Fig. 2.** Block diagram of a closed system.

By default, the LI-1b ( $W_{p1}$ ) and LI-2b ( $W_{p2}$ ) regulators implement proportional control laws with a unit gain, and the YY-12 compensator implements a matrix transfer function of

the form.

$$\begin{bmatrix} W_k^{11} & W_k^{12} \\ W_k^{21} & W_k^{22} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix},$$

which excludes its influence on the operation of closed systems.

To change the transfer functions of the regulators, move the mouse pointer over the symbol of the LI-1b or LI-2b regulator and press the left mouse button. This will lead to the appearance of the transfer function input window, the type of which is determined by the selection in the "Control" panel.

The application allows you to enter transfer functions of regulators of the form:

$$W(S) = \frac{\sum_{i=0}^n b_i s^i}{\sum_{i=0}^m a_i s^i} \text{ and } W(z) = \frac{\sum_{i=0}^n b_i z^{-i}}{\sum_{i=0}^m a_i z^{-i}}$$

where  $s$  is the differentiation operator,  $z = e^{sT_k}$ ,  $T_k$  is the quantization period,  $b_i$  and  $a_i$  are the coefficients of the polynomials of the numerator and denominator,  $n \leq m$  are the orders of the numerator and denominator.

The coefficients of the numerator and denominator of the transfer function are entered in square brackets separated by spaces in descending order of the index. A period is used as the decimal separator.

To enter the transfer function of the proportional link, it is necessary to specify the transfer coefficient in the numerator, enclosed in square brackets [K], and in the denominator, empty square brackets [ 19].

To enter a transfer function of the form:

$$W(S) = \frac{1}{T_i S} W(s) = \frac{1}{T_i s},$$

where  $T_i$  is the integration time constant, it is necessary to write [19] in the numerator and [T; 0]. in the denominator.

To change the matrix transfer function of the compensator, move the mouse pointer over the symbol YY-12 and press the left mouse button, which will lead to the appearance of the input window for the transfer function of the compensator. The application allows you to enter the transfer functions of the compensator of the form:

$$W(S) = \frac{\sum_{i=0}^n b_i s^i}{\sum_{i=0}^m a_i s^i} e^{-5z}, \text{ and } W(z) = \frac{\sum_{i=0}^n b_i z^{-i}}{\sum_{i=0}^m a_i z^{-i}} z^{-k}$$

where  $\tau$  is the delay time,  $k$  is the number of delay periods. Entering the transfer function coefficients is similar to that discussed earlier.

The program has a built-in lexical analyzer, which, in the event of an invalid input, issues a message to the user, where the rules for entering the transfer function coefficients are indicated [ 20].

To control the set values of the liquid levels in the tanks, next to the UGO regulators LC-1B and LC-2B, there are elements that allow you to change these values [21].

## 4 Conclusions

The developed virtual laboratory stand was tested during the 2020 pandemic and made it possible to carry out full-fledged laboratory work performed in the study of such courses as "Theory of automatic control", "Automation of technological processes", etc.

As a result of the introduction of a virtual laboratory stand in the educational process, it was possible not only to preserve, but also to improve the quality of education, since the developed application allows you to perform laboratory work at any time and in an unlimited

number, which is not possible when implementing an experiment on a stationary stand. And in view of the fact that in order to realize the maximum adequacy of the mathematical model, the program provides for the possibility of taking into account the influence of actuators on the regulation process, this application can be used for further development of an application - a "digital twin" for similar production processes.

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