doi: 10.1515/ecce-2015-0003
*Electrical, Control and Communication Engineering*
*2015/8*

# Research in Adaptronic Automatic Control System and Biosensor System Modelling

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***Abstract* – This paper describes the research on adaptronic systems made by the author and offers to use biosensors that can be later inserted into the adaptronic systems. Adaptronic systems are based, on the one hand, on the adaptronic approach when the system is designed not to always meet the worst condition, but to change the structure of the system according to the external conditions. On the other hand, it is an extension of common automatic control ad adaptive systems. So, in the introduction firstly the adaptronic approach and biosensor as a term is explained. Adaptive systems, upon which adaptronic ones are based, are also mentioned. Then the construction of biosensor is described, as well as some information is given about the classification of biosensors and their main groups. Also it is suggested to use lichen indicators in industry to control concentration of chemical substances in the air. After that mathematical models and computer experiments for adaptronic system and biosensor analysis are given.**

***Keywords* – Adaptation models; Biosensors; Modelling; Simulation.**

## I. Introduction

Adaptronic structures are also often called smart materials or intelligent structures. They can be defined using different paradigms, but two of them prevail. According to the technology paradigm, adaptronic structures are an “integration of sensors, actuators, and controls with a material or structural component”. The science paradigm refers adaptronic structures as “material systems that have intelligence and life-like features integrated in microstructure of the material in order to reduce the total mass and energy and produce an adaptive functionality”. The adaptronic approach is different from the classical engineering approach. The latter uses mathematical models to calculate the worst conditions that the mechanism or control system can undergo and the algorithm performs the same function and the same energy amount is used at each and every time. The adaptronic approach is inspired by the biological world. So, adaptronic systems work like natural and living systems. Actuators and motors behave like muscles, sensors resemble the “five senses” (hearing, sight, smell, taste and touch). Communication and computational systems (artificial intelligence) correspond to nerves, muscle control systems, brain and memory. So, the properties of the parts of the adaptronic systems should change in relation to external conditions [3], [4].

When speaking about adaptronic systems, we should not forget that they are examples of automatic control systems (ACS). There are different criterions of classification for such systems. According to the working principle, ACSs are divided into ACS on disturbance, ACS on deviation and combined ACS. According to the change during the output signal of setting device, the automatic control systems can be divided into automatic stabilization ACS, programmed ACS and tracking systems. As the words “adaptronic” and “adaptive” look similar, it is also worth mentioning adaptive or self-tuning systems.

But firstly biosensors that can be later inserted into adaptronic systems are described. Biosensor is a device that includes a biological sensing element that is connected or integrated with signal converter. The biosensor is used to create a digital electric signal that is proportional to the concentration of any chemical substance or combination of substances. This allows combining the sensitivity of biological systems with the computing power of computers. The technique of biosensors offers new effective means that offer radical changes in the approach to chemical analysis. The conception of biosensors is closely connected with the ideas of Leland Clark and his co-authors firstly developed in 1962. The authors offered that if ferments could be immobilized using electrochemical sensors, such “ferment electrodes” could improve the range of analytical opportunities of the basic sensor [15].

So, the term “biosensor” means a device that has a sensitive layer containing biological material: ferments, bacteria, DNA, tissues, receptors and so on. This layer reacts to the presence of the determined substance and generates a signal that depends on concentration of this component [15].

So, biosensor could be used in dangerous environments to control the level of dangerous substance. For example, the level of methane in mines or concentration of chemicals in the air in chemical industry may be controlled.

However, before getting to the process, the construction and classification of biosensor should be observed.

## II. Construction and Classification of Biosensors

The construction of a biosensor is very much like that of other chemical sensors. It consists of two converters – biochemical and physical [15].

Biochemical converter or biotransducer is a biological recognition element that converts the determined component (actually information on chemical bonds) into physical or chemical signal, but the physical converter allows registering this signal. Usage of biomaterial with unique properties allows selecting of needed substances from complex combinations without additional operations and reagents [15].

As physical transducers electrochemical, spectroscopic, thermal, piezoelectric, optical and other elements can be used [15].

The scheme of biosensor operation is shown in Fig. 1. The scheme is universal and can be used for every sensor where the reagent reacts to specific substance. To describe selective reactions between biological molecules, “key lock” mechanism is offered [15].

In biosensors the determining reagent is usually a macromolecule immobilized in membrane or chemically bound with the surface contacting with the solution of the determined substance. So, there is a specific reaction between the reagent and the definable component. It could be a direct reaction between the reagent and the substance (like antigen – antibody) or catalytic interaction of immobilized ferment with the definable substance with generation of easily defined product [15].

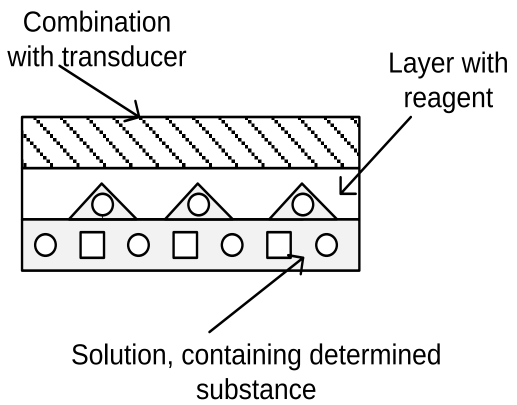


Fig. 1. Biosensor scheme [15].

Biosensors can be classified according to the type of transducer or biological recognizing element (bioreceptor) type. According to the transducer, biosensors can be divided into the following groups:

- electrochemical:
  - amperometric;
  - potentiometric;
  - conductometric;
- optical:
  - spectrophotometric;
  - fluorescent;
  - biosensors based on plasmon resonance;
  - biosensors based on liquid crystals.
- piezoelectric;
- calorimetric [16].

Amperometric sensors are mostly used nowadays.

According to the bioreceptor element, biosensors are divided into catalytic and affine [16].

Catalytic biosensors are based on ferments, tissue sections and microorganism cells. Their key feature is the consumption of the analyzed combination of substances in biochemical reactions according to the scheme: entering sample → contact between ferment and substrate → appearance of reaction product [16].

Affine sensors are based on antibodies/antigens, lectins, receptors of animal cells, nucleic acids. Their feature is that the analyzed substance is bound with a target in biosensor recognizing element, but not transformed and consumed. Also hybrid biosensors are known that combine affine interaction and fermentative signal amplification [16].

The main features of biosensor analysis that distinguish it from classical physical-chemical methods of analysis are:

- addition of reagents to the explored sample usually is not needed for analysis;
- simplicity of analysis;
- low cost of analysis because of simple devices used;
- high sensitivity and specificity because of the use of biological material that makes transformation of some substances, changes its properties in contact with biologically active compounds or creates easily identified combinations with the explored material;
- multiplicity – the determined substance can be defined many times;
- opportunity to be used in house or field conditions [16].

Because of these qualities, it could be more efficient to use biosensors instead of other chemical sensors in different branches of industry, where the concentration of substrates should be determined.

Nowadays lichen indication monitoring is developing to control the chemical pollution of the air. Lichens are very sensitive to specific chemicals and can be used either on their own or in biosensors. This method is widely used in urban areas. However, the new idea is to use lichens in biosensors that control the concentration of different substances in industry. Of course the properties of lichens should be explored in order to find which of them reacts, for example, on methane. But in such a case the control system could be much simpler than the system with traditional chemical sensors [8], [15].

After the classification of biosensors it is worth giving structural schemes and mathematical models of both adaptronic and biosensor control systems.

## III. Structural Schemes and Mathematical Models for Adaptronic Systems

The distinguishing feature of the automatic stabilization ACS is the constant value of the sum of setting device output signals:

$$\sum_{i=1}^{n} x_{out.set} = const \quad , \tag{1}$$

where $x_{out\ set}$ is the setting device output signal [12].

Such systems are used for technologies of continuous production where the technological mode does not change during many days [12].

The distinguishing feature of the programmed ACS is the change of the sum of setting signals according to the predefined time function that is a program. [12]

$$\sum_{i=1}^{n} x_{out.set} = f(t), \qquad (2)$$

where $f(t)$ is the time function.

The programmed ACSs are used to control periodic processes, the program is usually written into the microprocessor, microcontroller or PLC [12].

In tracking systems the output signals of setting device are not predefined, so they can be random values:

$$\sum_{i=1}^{n} x_{out.set} = \text{var}, \qquad (3)$$

where *var* is the variable (changing) parameter.

The main advantage of ACS working on deviation is that it compensates the influence of any disturbance that has caused the deviation of the signal $\pm\Delta X_{out}$ while changing the input signal using negative feedback. The drawback of such ACS is that the controller does not work before the deviation and it not only has to compensate the disturbance, but also to make the deviation between the set and output parameter equal to zero [12].

If the ACS works on disturbance, it is compensated by the controller before it violates the technological mode of the object, but it cannot compensate other disturbances and the system does not have the feedback that connects the input and output signals [12].

Combined ACSs do not have many disadvantages of the previously mentioned systems. Their structural scheme is shown in Fig. 2. [12].

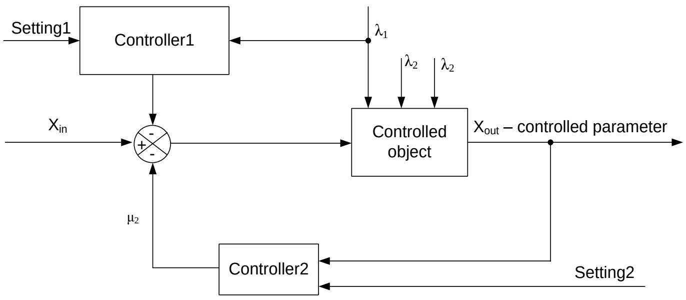


Fig. 2. Structural scheme of combined ACS [12].

Controller1 compensates the strongest disturbance λ1. To compensate other disturbances Controller2 is put into negative feedback, so such system uses the principle of both ACS on deviation and ACS on disturbance [12].

The structural scheme of a system that reacts on many disturbances is close to that of adaptive self-tuning control systems. A self-tuning ACS should provide the necessary quality of process control while changing properties of the controlled object or controller elements as well as while changing the characteristics of disturbance. The structural system of such system with open self-tuning loops is shown in Fig. 3. [11].

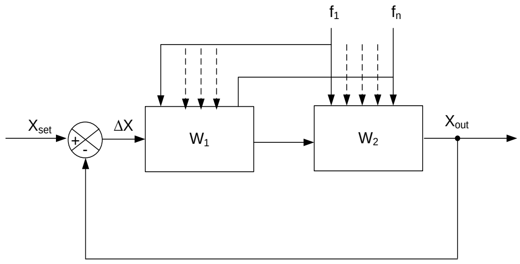


Fig. 3. Structural scheme of self-tuning ACS [11].

Here, $X_{set}$ is the input signal (the set value of the measured parameter), $X_{out}$ is the output signal of the system (real value of the measured parameter), $\Delta X$ is system error (deviation) – the difference between the set and the real value of the measured parameter. $W_1$ and $W_2$ are transfer functions of the parts of the system. Here $W_2$ is the transfer function of the object and controller and $W_1$ is the transfer function of a block that could be called a correction device [11].

Under the disturbances $f_1,\ldots, f_n$ the transfer function $W_2$ changes. To compensate these changes the same disturbances are passed to the correction device in order to change its transfer function $W_1$ [11].

The transfer function $\Phi_{ACS}$ of the closed-loop system is:

$$\Phi_{ACS} = \frac{W_1 \cdot W_2}{1 + W_1 \cdot W_2}, \qquad (4)$$

where $W_1$ is the transfer function of the correction device and $W_2$ is the transfer function of the object and controller.

To preserve this function constant, the condition $W_1 W_2$ = *const* should be observed. So, the transfer function of the correction device should be changed according to (5):

$$W_1 = \frac{W_{10} \cdot W_{20}}{W_2}, \qquad (5)$$

where $W_{10}$ and $W_{20}$ are transfer functions for the beginning states of the system [11].

Besides the adaptive systems offered above, some other adaptive algorithms can be offered. The structural scheme of the adaptive system is seen in Fig. 4.

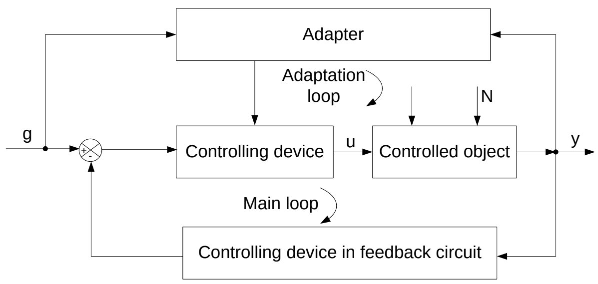


Fig. 4. Structural scheme of adaptive system.

In the system mentioned above $g$ is the input signal (a set value of the measured parameter), $y$ is the output signal of the system (real value of the measured parameter), $u$ is the signal that is passed from the controlling device to the controlled object and $N$ is disturbances for the controlled object.

An adapter is the device that realizes adaptation algorithms. The controller consists of two parts: a controlling device (series of correction loop) and a controlling device in feedback circuit (parallel correction loop). The first part contains tunable parameters, the second is unchangeable. The object with the controller form the main regulation loop, the adapter with the changeable part of controller form the adaptation (or self-tuning) loop. If the controlling circuit is set by the reference model, the structural scheme looks like in Fig. 5.

In this system β is the impact of adapter on the controlling device, $y_m$ is the output of the reference model and $e$ is the error (difference between the real and reference output signal).

Adaptronic systems differ from adaptive systems – in response to external disturbances they change the structure of the controlled object. To perform it a special device called adapter is used. It consists of adaptronic sensors, actuators and a controlling device. Several adapters may be applied to the same object reacting to different external parameter changes. The structural scheme of an adaptronic system can look like in Fig. 6.

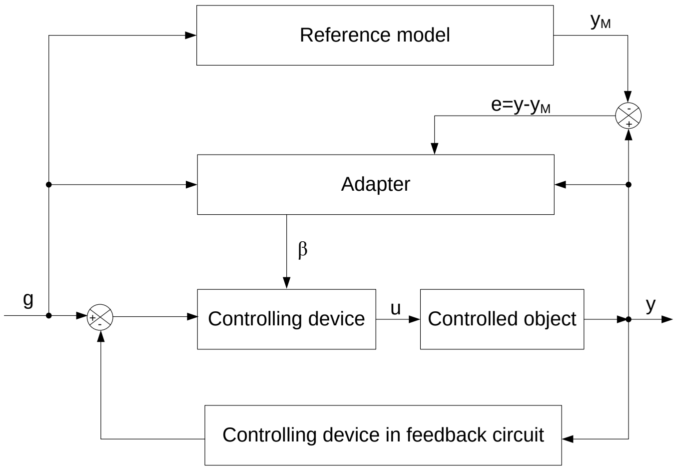


Fig. 5. Structural scheme of adaptive system with reference model.

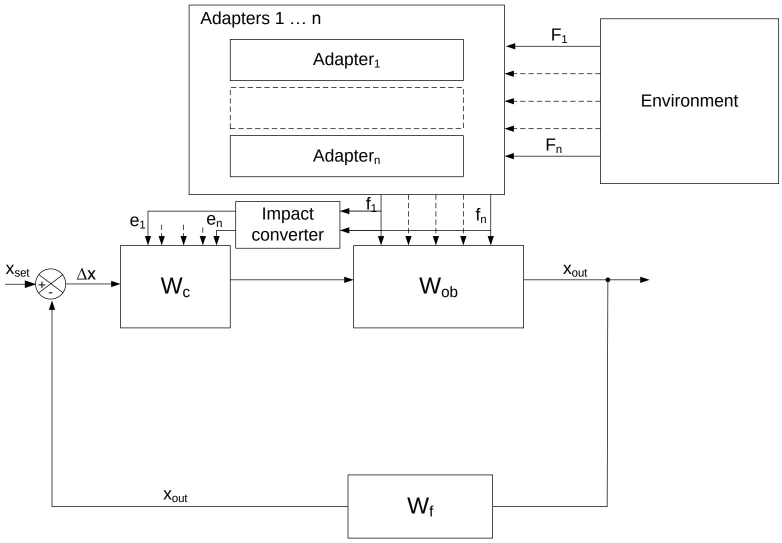


Fig. 6 Structural scheme of adaptronic system.

The system has the main loop that consists of the controller transfer function $W_c$, the controlled object transfer function $W_{ob}$ and the negative feedback transfer function $W_f$. It takes the setting signal $x_{\text{set}}$, compares it with the output signal of the system $x_{\text{out}}$ and passes the deviance (error) $\Delta x$ to the controller that processes it and passes further to the controlled object. If we assume that $W_f = 1$ and the feedback just inverts the output signal of the control system, (4) and (5) can be applied to the system and it could be rewritten as (6):

$$W_c = \frac{W_{c0} W_{ob0}}{W_{ob}}, \tag{6}$$

where

$W_c$ controller transfer function;

$W_{c0}$ controller transfer function without adaptation;

$W_{ob}$ controlled object transfer function;

$W_{ob0}$ controlled object transfer function without adaptation.

However, this system differs from the adaptive system shown in Fig. 1. The system has an adapting block, here shown as the combination of different adapting devices or adapters that take the disturbances $F_1...F_n$ from the environment, process them and pass the impacts $f_1...f_n$ to the controlled object that change its internal structure, so the transfer function of the object $W_{ob}$ changes and converted impacts $e_1...e_n$ are applied to the transfer function of the controller $W_c$ to preserve (6). Each adapter can be represented as a block consisting of a sensor, actuator and a controlling unit (though actually the adapting block should contain a controller that processes several parameters). Such structure is shown in Fig. 7.

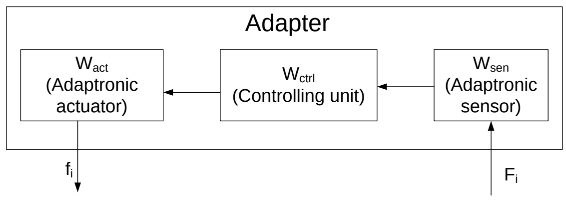


Fig. 7. Structural scheme of adapter.

The sensor measures the parameter $F_i$, for example, temperature or pressure and converts it into electrical signal (transfer function $W_{sen}$). Then the signal is processed by the controlling unit $W_{ctrl}$ and applied to the actuator $W_{act}$ that performs mechanical impact $f_i$. So, the adapter can be treated as open-loop control system with the transfer function $W_{adapt}$ according to (7):

$$W_{adapt} = W_{sen} \cdot W_{ctrl} \cdot W_{act}\,, \tag{7}$$

where $W_{sen}$ is the sensor transfer function, $W_{ctrl}$ is the controlling unit transfer function and $W_{act}$ is the actuator transfer function.

If Laplace operator s as in automatic control theory is used, the object is considered as the first order aperiodic block with the transfer function

$$W_{ob0}(s) = \frac{k_{ob}}{1 + T_{ob} \cdot s}\,, \tag{8}$$

where $k_{ob}$ is the object proportionality coefficient, $T_{ob}$ is the object time constant and $s$ is the Laplace operator.

The controlling block is the PI controller with the transfer function (9):

$$W_{c0}(s) = k_p + \frac{1}{T_i \cdot s}\,, \tag{9}$$

where $k_p$ is the proportionality coefficient and $T_i$ is the integration time constant.

The transfer function of the whole system before adaptation is (10):

$$\Phi_{ACS0}(s) = \frac{k_p \cdot k_{ob}}{T_i \cdot T_{ob} \cdot s^2 + (k_p \cdot k_{ob} + 1) \cdot T_i \cdot s + k_p \cdot k_{ob}}. \tag{10}$$

For the first experiment, to simplify the model, it can be assumed that two adapters are applied, the first of them ($f_1$) adds a constant to $k_{ob}$, the second ($f_2$) adds a constant to $T_{ob}$. So, the transfer function of the controlled object will be:

$$W_{ob}(s) = \frac{(k_{ob} + k_{adapt1})}{1 + (T_{ob} + T_{adapt2}) \cdot s}, \tag{11}$$

where $k_{adapt1}$ is the impact of the first adapter and $T_{adapt2}$ is the impact of the second adapter.

To satisfy the condition $W_{ob}W_c = const$, taking into account the transfer function before adaptation, (3) should be rewritten as (12):

$$\begin{aligned} W_c &= \frac{(k_p \cdot T_i \cdot s + 1) \cdot k_{ob} \cdot ((T_{ob} + T_{adapt}) \cdot s)}{T_i \cdot s \cdot (1 + T_{ob} \cdot s) \cdot (k_{ob} + k_{adapt1})} = \\ &= \frac{(k_p \cdot T_i \cdot s + 1) \cdot k_{ob} \cdot (T_{ob} + T_{adapt})}{T_i \cdot (1 + T_{ob} \cdot s) \cdot (k_{ob} + k_{adapt1})}. \end{aligned} \tag{12}$$

In this case it is easier to preserve the whole transfer function (10) constant. So, to compensate the influence of the first adapter, (13) should be true:

$$k_p \cdot k_{ob} = (k_p + k_{padapt1}) \cdot (k_{ob} + k_{adapt1}), \tag{13}$$

where $k_{padapt1}$ is the value that is added to the proportionality constant of the PI controller.

$k_{padapt1}$ can be found from (14):

$$\begin{aligned} k_{padapt1} &= \frac{k_p \cdot k_{ob} - k_p \cdot (k_{ob} + k_{adapt1})}{(k_{ob} + k_{adapt1})} \\ &= \frac{-k_p \cdot k_{adapt1}}{k_{ob} + k_{adapt}}. \end{aligned} \tag{14}$$

To compensate the influence of the first adapter, (15) should be true:

$$\begin{aligned} &T_i \cdot T_{ob} \cdot s^2 + (k_p \cdot k_{ob} + 1) \cdot T_i \cdot s + k_p \cdot k_{ob} = \\ &= (T_i + T_{iadapt2}) \cdot (T_{ob} + T_{adapt2}) \cdot s^2 + \\ &+ (k_p \cdot (k_{ob} + k_{adapt1}) + 1) \cdot (T_i + T_{iadapt2}) \cdot s + \\ &+ k_p \cdot (k_{ob} + k_{adapt1}), \end{aligned} \tag{15}$$

where $T_{iadapt2}$ is the value that is added to the integration time constant of PI controller and $T_{iadapt2}$ can be found from (16):

$$T_{iadapt2} = \frac{-(T_i \cdot T_{adapt2} \cdot s^2 + k_p \cdot k_{adapt1})}{(T_{ob} + T_{adapt2}) \cdot s^2 + (k_p \cdot (k_{ob} + k_{adapt1}) + 1) \cdot s}. \tag{16}$$

The next mathematical model focuses on the adapting mechanism for an adaptronic system.

In adaptronic systems the material used in sensors in actuators plays an important role. Actuators change mechanical characteristics of adaptronic systems in response to the changes in electric or magnetic field or temperature. Such materials are mostly used in actuators: shape memory alloys, piezoelectric materials, magnetostrictive materials, electrorheological fluids and magnetorheological fluids. Sensors are operated for different purposes: vibration detection and dampening, acoustic attenuation, intelligent processing, damage detection and control and others. Sensors can be added as external ones or incorporated within the structure through manufacturing. For such purposes optical fibers or piezoelectric materials that produce electrical charges as a reaction to mechanical stress are used. Materials can also change their properties because, for example, of changes in temperature [4].

As examples of real world applications where adaptronics can be used, devices for vibration reduction, noise reduction, and structural health monitoring can be mentioned. They are used, for example, in vehicle engineering, machine tools and plant engineering and construction, medical technology, aerospace, optics and military technology [1].

Disturbance from the environment is passed to the sensor that generates the electric signal. Then this signal is passed to the controlling unit, processed in it and passed to the actuator that changes the mechanical properties of the object [5].

To simplify the model, the sensor and the actuator are considered as first order aperiodic blocks, the controlling unit is the PI controller. So, if the Laplace operator $s$ as in automatic control theory is used, their transfer functions will be (17), (18) and (19):

$$W_{sen}(s) = \frac{k_{sen}}{1 + T_{sen} \cdot s}\,, \tag{17}$$

$$W_{act}(s)=\frac{k_{act}}{1+T_{act}\cdot s}, \qquad (18)$$

$$W_{ctrl}(s)=k_{ctrl}+\frac{1}{T_{ctrl}\cdot s}, \qquad (19)$$

where

$k_{sen}$ sensor proportionality coefficient;

$T_{sen}$ sensor time constant;

$s$ Laplace operator;

$k_{act}$ actuator proportionality coefficient;

$T_{act}$ actuator time constant;

$k_{ctrl}$ adapter controlling unit proportionality coefficient;

$T_{ctrl}$ adapter controlling unit integration time constant [5].

So, the transfer function of the whole adapter is:

$$W_{adapt}(s)=\frac{k_{sen}\cdot k_{act}(k_{ctrl}T_{ctrl}s+1)}{(1+T_{sen}\cdot s)(1+T_{act}\cdot s)T_{ctrl}\cdot s}=\frac{k_{sen}\cdot k_{act}k_{ctrl}T_{ctrl}s+k_{sen}\cdot k_{act}}{T_{ctrl}\cdot s+(T_{act}+T_{sen})T_{ctrl}s^2+T_{sen}T_{act}T_{ctrl}s^3} \qquad (20)$$

To simplify the model, the transfer functions of the controller and the controlled object are constants:

$$W_{ob0}(s)=k_{ob} \qquad (21)$$

$$W_{c0}(s)=k_c, \qquad (22)$$

where $k_{ob}$ is the object proportionality coefficient and $k_c$ is the controller proportionality coefficient [5].

So, the transfer function of the whole system before adaptation is (23):

$$\Phi_{ACS0}(s)=k_p\cdot k_{ob}. \qquad (23)$$

To simplify the model it can be assumed that one adapter is applied ($F_1$), it is multiplied with $W_{adapt}$ and added to $k_{ob}$. So the object transfer function will be:

$$W_{ob}(s)=k_{ob}+\frac{k_{sen}\cdot k_{act}k_{ctrl}T_{ctrl}s+k_{sen}\cdot k_{act}}{T_{ctrl}\cdot s+(T_{act}+T_{sen})T_{ctrl}s^2+T_{sen}T_{act}T_{ctrl}s^3}F_1 \qquad (24)$$

To satisfy the condition $W_{ob}W_C = const$, taking into account the transfer function before adaptation, (3) should be rewritten as (25):

$$W_c(s)=\frac{k_p\cdot k_{ob}(T_{ctrl}\cdot s+(T_{act}+T_{sen})T_{ctrl}s^2+T_{sen}T_{act}T_{ctrl}s^3)}{k_{ob}(T_{ctrl}\cdot s+(T_{act}+T_{sen})T_{ctrl}s^2+T_{sen}T_{act}T_{ctrl}s^3)+(k_{sen}\cdot k_{act}k_{ctrl}T_{ctrl}s+k_{sen}\cdot k_{act})F_1} \qquad (25)$$

To simplify (25) the nominator will be denoted as $k_p{\cdot}A$ and the denominator will be denoted as B:

$$A=k_{ob}(T_{ctrl}\cdot s+(T_{act}+T_{sen})T_{ctrl}s^2+T_{sen}T_{act}T_{ctrl}s \qquad (26)$$

$$B=k_{ob}(T_{ctrl}\cdot s+(T_{act}+T_{sen})T_{ctrl}s^2+T_{sen}T_{act}T_{ctrl}s^3)+(k_{sen}\cdot k_{act}k_{ctrl}T_{ctrl}s+k_{sen}\cdot k_{act})F_1 \qquad (27)$$

The value $\Delta W_C$ that is added to $k_p$ will be:

$$\Delta W_c=\frac{k_pA}{B}-k_p=\frac{k_p(A-B)}{B}. \qquad (28)$$

For simulation $\Delta W_c$ could also be calculated as:

$$\Delta W_c(s)=\frac{k_pk_{ob}}{(k_{ob}+W_{adapt}(s)\cdot F_1)}-k_p=\frac{-k_pW_{adapt}(s)\cdot F_1}{(k_{ob}+W_{adapt}(s)\cdot F_1)} \qquad (29)$$

After structural schemes and mathematical models, computer simulations should be performed [5].

## IV. Mathematical Model and Structural Scheme of Biosensor System

After the overall description of biosensor, a mathematical model can be created.

The initial speed of fermentative reaction from substrate combination is described by Michaelis-Menten equation (30):

$$V=\frac{V_{\max}S}{K_M+S}, \qquad (30)$$

where

$V$ speed of fermentative reaction;

$V_{\max}$ maximum speed of fermentative reaction with full saturation of substrate in the ferment;

$K_M$ Michaelis constant;

$S$ concentration of substrate [16].

The substrate is converted to a product in a catalytic event involving the transition state formation. So, the enzyme substrate complex $C$ combines the substrate $S$ and enzyme $E$. So, such biosensors have an enzyme-substrate interaction. There are two main models for experiments on them: a free enzyme model and immobilized enzyme model. Here the mathematical model for free enzyme model is shown [7].

This model analyzes the reaction rates of species diffusing together. The reactions of free enzyme model do not happen on the electrode surface. The enzymes are placed in the test tube with substrates diffuse through the test tube. The substrates react with enzymes at $t = 0$. As they react, the samples $C$ and $P$ are formed. These species diffuse to the electrode at $t > 0$. So, at that point $(x = 0)$ current measurements are taken. The reaction follows the Michaelis-Menten scheme, that can be rewritten as (31):

$$E+S\underset{k_{-1}}{\overset{k_1}{\longleftrightarrow}}C\xrightarrow{k_{cat}}E+P, \qquad (31)$$

where

$E$ enzyme;

$S$ substrate;

$C$ complex;

$P$ reaction product;

$k_1$, $k_{-1}$, $k_{cat}$ rates of reactions [6], [7], [14].

At the time $t < 0$ substrate is fixed to the top of the test tube. At $t = 0$ both species are released by a conduction medium and diffusion begins in tube. When the diffusion medium $R$ is a bounded domain in $V$, the reaction diffusion equations are supplemented by suitable border conditions on the border surface $\partial S$ [7].

The border conditions depend on the physical mechanism surrounding the diffusion medium. On the border they often depend on the material properties both in the diffusion medium and out of it [7].

When the flux across the border surface is prescribed, the border condition becomes (32):

$$\frac{\partial u}{\partial v} = h(x,t) \quad , \tag{32}$$

were $h$ is the rate of flow of density and $\partial u/\partial v$ is the directional derivative of $u$ in the direction of $v$ [14].

Also homogeneous Neumann border condition can be used:

$$\frac{\partial u}{\partial v} = 0 \ \ (t > 0, x \in \partial S) \ . \tag{33}$$

The physical meaning of this equation is that the border surface is completely insulated so that there is no flux across the border (the zero flux border condition). This border condition can be used on a free surface of the diffusion medium as chemical samples cannot leave the solution [7].

Then differential conditions can be constructed on the principle of conservation which is governing the behavior of relevant chemical samples. The substrate hydrogen peroxide is free to diffuse throughout the domain, so (34), (35), (36) and (37) are true as in [7]:

$$\frac{\partial S}{\partial T} = D_s \frac{\partial^2 S}{\partial X^2} + k_{-1}C - k_1 ES \ , \tag{34}$$

$$\frac{\partial P}{\partial T} = D_p \frac{\partial^2 P}{\partial X^2} + k_{cat}C \ , \tag{35}$$

$$\frac{\partial E}{\partial T} = D_e \frac{\partial^2 E}{\partial X^2} + (k_{-1} + k_{cat})C - k_1 ES \ , \tag{36}$$

$$\frac{\partial C}{\partial T} = D_c \frac{\partial^2 C}{\partial X^2} - (k_{-1} + k_{cat})C - k_1 ES \ . \tag{37}$$

Zero-flux border conditions are as in [7]:

$$D_s \frac{\partial^2 S}{\partial X^2}(L,t) = 0 \quad D_p \frac{\partial^2 P}{\partial X^2}(L,t) = 0 \ , \tag{38}$$

$$D_e \frac{\partial^2 E}{\partial X^2}(L,t) = 0 \quad D_c \frac{\partial^2 C}{\partial X^2}(L,t) = 0 \ , \tag{39}$$

$$D_s \frac{\partial^2 S}{\partial X^2}(0,t) = 0 \quad D_p \frac{\partial^2 P}{\partial X^2}(0,t) = 0 \ , \tag{40}$$

$$D_e \frac{\partial^2 E}{\partial X^2}(0,t) = 0 \quad D_c \frac{\partial^2 C}{\partial X^2}(0,t) = 0 \ . \tag{41}$$

Initial conditions are as in [7]:

$$P(x,0) = 0 \ \ E(x,0) = E(0) \ \ C(0) = 0 \ . \tag{42}$$

From the law of mass conservation (14) is true:

$$E = E_0 - C \ , \tag{43}$$

where $E$ is the total amount of the enzyme present on the electrode. Also $S_0(x) = S_0$ if $x = L$, otherwise it is 0 [7].

As it is seen, the role of biosensor is to detect the concentration of a specific substrate in the combination of substances. So, for this paper a system will be modelled that generates a signal if concentration of the substance is greater than allowed. To simplify the model, we will not go deeply into chemistry, but just make a structural scheme that has a combination of substances and multiple sensing elements. Each of these elements reacts to the concentration of the specific substance. The structural scheme of the system used in experiments is shown in Fig. 8. In this scheme we have a combination of substances that includes 3 substrates that have to be detected. Their concentration is $S_1$, $S_2$ and $S_3$ respectively. They are inputs of biosensors.

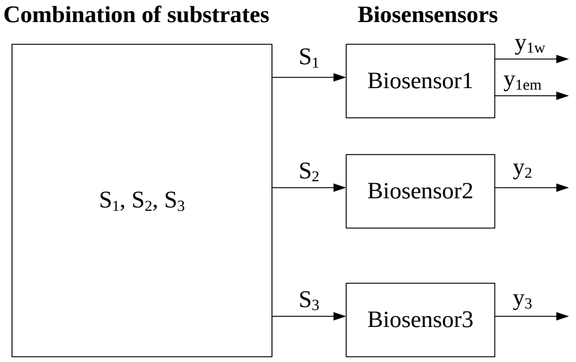


Fig. 8. Structural scheme for biosensor system with 3 biosensors.

Biosensor1 has two output signals, which are regulated from (44) and (45):

$$y_{1w} = \begin{cases} 0, S_1 < S_{1w} \\ 1, S_1 \geq S_{1w} \end{cases} , \tag{44}$$

$$y_{1em} = \begin{cases} 0, S_1 < S_{1em} \\ 1, S_1 \geq S_{1em} \end{cases} , \tag{45}$$

where

$S_{1w}$ warning concentration of the 1st substrate;

$S_{1em}$ emergency concentration of the 1st substrate;

$y_{1w}$ output signal for warning concentration of the 1st substrate;

$y_{1em}$ output signal for emergency concentration of the 1st substrate.

Because of the Michaelis-Menten equation (30), firstly $S_{1w}$ is detected, then $S_{1em}$. So, if emergency concentration is reached, both $y_{1w}$ and $y_{1em}$ signals are active.

The output signals of biosensors 2 and 3 are obtained from (46) and (47):

$$y_2 = \begin{cases} 0, S_2 < S_{2em} \\ 1, S_2 \geq S_{2em} \end{cases} , \tag{46}$$

$$y_3 = \begin{cases} 0, S_3 < S_{3em} \\ 1, S_3 \geq S_{3em} \end{cases} , \tag{47}$$

where

$S_{2em}$ emergency concentration of the 2nd substrate;

$S_{3em}$ emergency concentration of the 3rd substrate;

$y_2$ output signal for the 2nd substrate;

$y_3$ output signal for the 3rd substrate.

According to the structural scheme and mathematical model the working algorithm of control system with biosensor can be derived. It is seen in Fig. 9. Then the description follows.

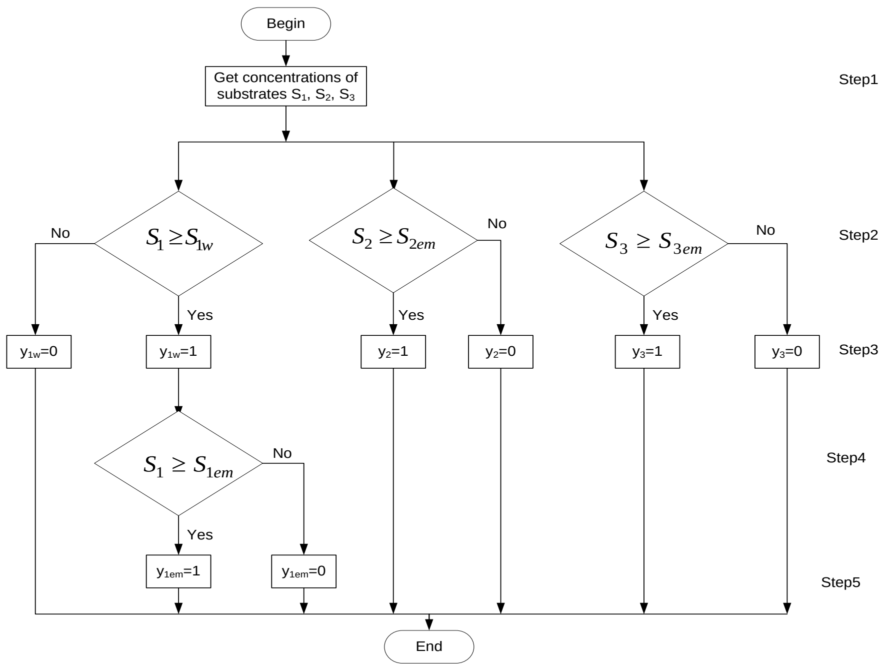


Fig. 9. Algorithm of biosensor control system.

Step 1. Input signals (concentrations of substrates) $S_1$, $S_2$, $S_3$ are entered.

Step 2. Input signals $S_1$, $S_2$, $S_3$ are compared with predefined values: $S_{1w}$ (warning concentration), $S_{2em}$ and $S_{3em}$ (emergency concentrations).

Step 3. If input signals are greater or equal to corresponding predefined values, output signals $y_{1w}$, $y_2$ or $y_3$ are set active, for $y_{1w}$ proceed to Step 4, for $y_2$ or $y_3$ – go to End,

else

output signals $y_{1w}$, $y_2$ or $y_3$ are set inactive, go to End.

Step 4. Input signal $S_1$ is compared with predefined value: $S_{1em}$ (emergency concentration).

Step 5. If input signal is greater or equal to corresponding predefined value, output signal $y_{1em}$ is set active, go to End,

else

output signal $y_{1em}$ is set inactive, go to End.

After that computer simulation may be made based on (44)–(47).

## V. Computer Simulations of Adaptronic System

The interface of the computer simulation of adaptronic system model is shown in Fig. 10.

The reaction of the output signal of the system xout in time on the setting signal *x*set = 1 is displayed in scope. Firstly, the reference signal without disturbances F1 and F2 is shown.

The coefficients of the transfer functions *Wc* and *Wob* are selected to have an overshoot less than 10 % and to have the static error of the system equal to zero. Here:

$k_p$ = 1;

$T_i$ = 1;

$k_{ob}$ = 20;

$T_{ob}$ = 3.

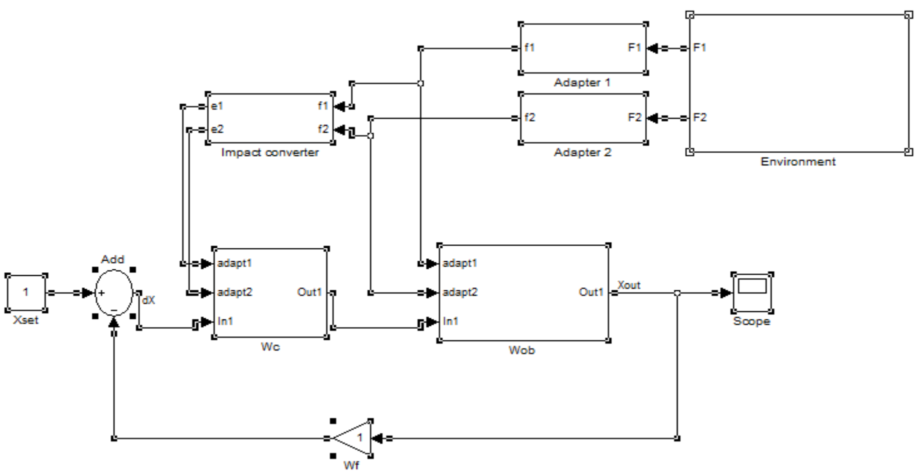


Fig. 10. Interface of adaptronic system computer model.

To simplify the model, the function F2 that changes the time constants of the object and controller is set to zero and only F1 that changes the proportionality constant is operated.

The curve of such system is shown in Fig. 11.

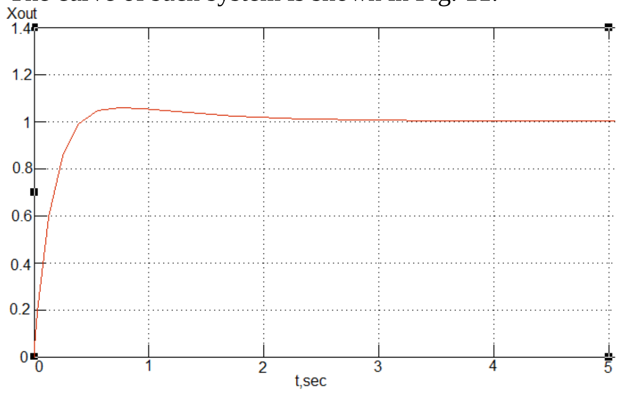


Fig. 11. The curve of control system without adaptation.

The curve of $x_{out}$ with F1 = 10 and the function of adapter1 $W_{adapt1} = k1 = 2$ is shown in Fig. 12.

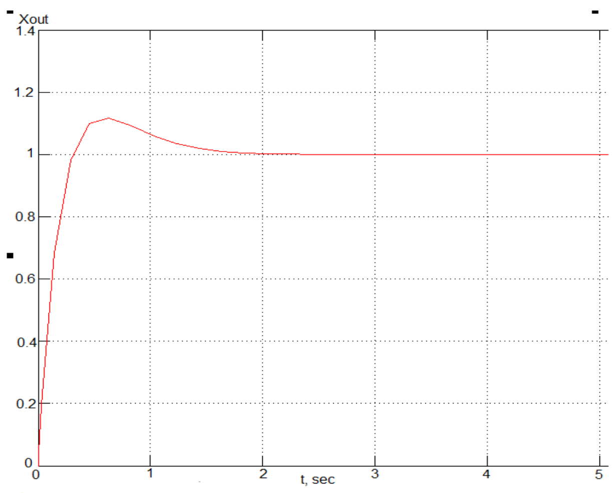


Fig. 12. The curve of control system with F1 = 10 and $k1 = 2$.

The curve of $x_{out}$ with F1 = 20 and the function of adapter1 $W_{adapt1} = k1 = 2$ is shown in Fig. 13.

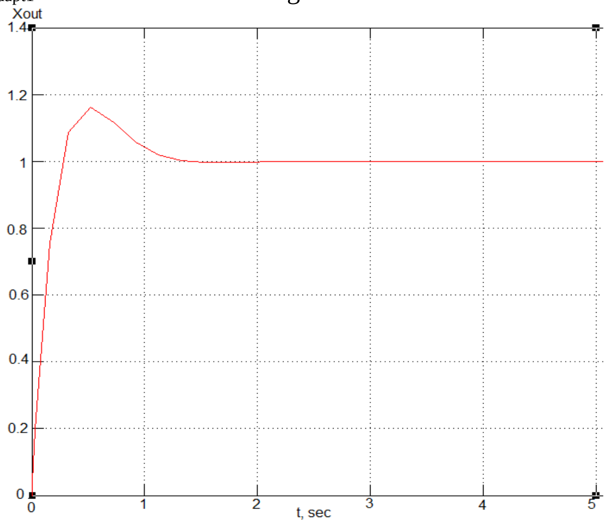


Fig. 13. The curve of control system with F1 = 20 and $k1 = 2$.

## VI. Computer Simulation of the Control System with Biosensor

The interface of computer simulation for a biosensor system is shown in Fig. 14.

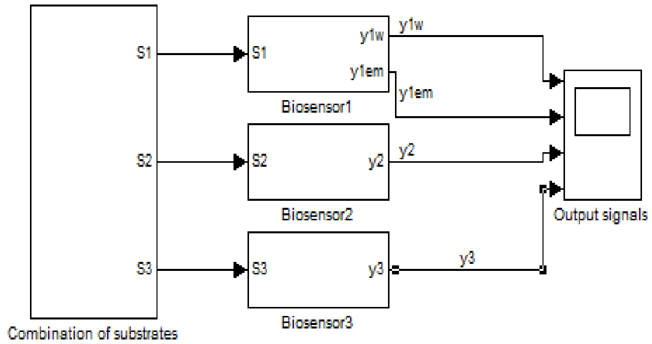


Fig. 14. Computer simulation interface for a biosensor system.

Concentration can be measured in different units, here it is in mol/L. So, it is assumed, that the warning concentration of $S_1$ is $S_{1w} = 5$ (mol/L), the emergency concentration of $S_1$ is $S_{1em} = 10$ (mol/L), the emergency concentration of $S_2$ is $S_{2em} = 10$ (mol/L), the emergency concentration of $S_3$ is $S_{3em} = 10$ (mol/L). The values of output signals that correspond to different concentration of $S_1$, $S_2$ and $S_3$ are shown in Table I.

TABLE I

Output Signals for Different Concentrations of $S_1$, $S_2$ and $S_3$

| **Concentration** | $y_{1w}$ | $y_{1em}$ | $y_2$ | $y_3$ |
|---|---|---|---|---|
| $S_1 = 0$ (mol/L), $S_2 = 0$ (mol/L), $S_3 = 0$ (mol/L) | 0 | 0 | 0 | 0 |
| $S_1 = 7$ (mol/L), $S_2 = 0$ (mol/L), $S_3 = 0$ (mol/L) | 1 | 0 | 0 | 0 |
| $S_1 = 12$ (mol/L), $S_2 = 12$ (mol/L), $S_3 = 12$ (mol/L) | 1 | 1 | 1 | 1 |

If $S_1 = 0$, $S_2 = 0$ and $S_3 = 0$, all output signals are seen in Fig.15. All output signals are equal to zero.

If concentration $S_1$ is set to 7 (mol/L), it exceeds $S_{1w}$. The output signal $y_{1w}$ is active (its value is “1”). The value of other output signals stay at “0” (inactive).

If $S_1$, $S_2$, $S_3$ are set to 12 (mol/L, all the four output signals are active (their values are “1”).

Thus, the computer simulation shows how biosensors react to concentration of specific substrates.

## VII. Conclusion

This paper shows that adaptronic control systems are very similar to adaptive systems that are widely known, but there are some differences between them:

- Adaptive or self-tuning systems usually just change the control parameters while adapting to disturbances. Adaptronic control systems change the structure of the controlled object.
- Adaptronic systems change their structure as a reaction to

changes of the environment parameters, that may not directly disturb the object, but are measured by adaptronic sensors.

So, the first novelty of this paper is that the well-known adaptive system is replaced by an adaptronic system.

A mathematical model was derived for adaptronic systems. It is based on equations for adaptive systems, but in this case the changes in the controlled object are primary, and the controller algorithm should adapt to changes in the object that are mathematically written as the adjustment of the controlled object transfer function.

The computer simulation shows that the adaptronic control system can preserve the same output signal under the impact of the environment, though the transition process could be worse.

The paper also describes usage of biosensors to control concentration of different substrates in the air that can be used for security purposes.

Other novelties of the paper are:

- Suggestion to use lichens in biosensors that control concentration of different substances in industry;
- A new structural scheme and mathematical model for the biosensor control system;
- A new algorithm derived for the biosensor control system based on structural scheme.

The computer simulation shows that a biosensor can control concentration of substrate and generate an output signal if it exceeds certain levels. The biosensor in the simulation allows controlling two levels of substrate concentration. Biosensors also can generate a signal that is proportional to concentration of substrate, so continuous control also is possible but it is a topic for new experiments.

The structural schemes simulated here are universal, each block can be developed to produce more complicated equations for the mathematical model. The universality of these models allows to develop physical models of adaptronic control system and a control system with biosensors, taking into account their internal structure. In further research adaptronic systems and biosensors will be combined.

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