

Task of Optimal Control of Gas Exchange in System "Artificial Lungs - Self-contained Breathing Apparatus"

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Abstract—The structure of the predictive control system of the test facility "Artificial lungs" is developed. The statement of the task of optimal control of actuating mechanisms of the test facility "Artificial lungs" is formalized: the equation of object control in the form of differential equations is formulated, vectors states, controls, and restrictions on their components are found, optimality criterion in the form of a generalized functional work is determined. The algorithm for forming the task is proposed. The method of solving the problem of optimal control and the algorithm for optimal control of the supply and removal of gases from the system "Artificial lungs - Self-contained breathing apparatus" is chosen. The proposed algorithm will allow controlling gas volumes with a given accuracy and with minimal energy consumption for control.

Keywords—artificial lungs; contained breathing apparatus; optimal control; A.A. Krasovsky's functional; predictive algorithm

I. INTRODUCTION

Self-contained breathing apparatus (SCBA), working chemical oxygen are used for protection of the human respiratory system in a variety of extreme situations: on and under the earth, in space, on and under the water.

Since SCBA tests on humans for many reasons are possible only to a limited extent, and in some cases they can be unsafe, these tests are made in specialized test facilities called "Artificial Lungs" (AL).

Currently, different types of automated AL facilities are used for SCBA trials [1-3]. The main objective of AL facility control systems when simulating human breath is the realization of a given mode of AL functioning, adequately reflecting psychophysiological state of a person, characterized by the values of various parameters (pulmonary ventilation, pressure, temperature, humidity, flow and concentration of gases, breathing pneumotachogram, etc.). The existing control systems of AL facilities do not allow one to reproduce human breath accurately, in particular, to simulate oxygen

consumption by a human being in a wide range of values of the respiratory rate (ratio of the volume of released carbon dioxide and consumed oxygen), to simulate human respiration pneumotachograms [1-4].

The object of the study in this paper is an automated AL test facility, where the oxygen consumption is simulated as a release of the calculated volume of gas-air mixture (GAM) into the atmosphere with simultaneous supply of nitrogen and carbon dioxide in amounts that are removed when GAM release into the atmosphere [4]. Let a three-component mixture of gases O_2 , CO_2 , N_2 circulates in the AL. The test facility is equipped with dosing pistons with linear electrical actuators to release the GAM and feed carbon dioxide and nitrogen in the facility. These devices must operate in synchronization with the drive of breathing simulator, which reproduces various breathing pneumotachograms (sine, triangular, trapezoidal, etc.), with predetermined frequency n and depth V_d . The release of GAM and feeding of respective gases is carried out in the inhalation phase. Since SCBA trials in AL facility involve measuring concentrations of inhaled and exhaled gases by gas analyzers, which have a certain delay and errors, the AL control system is supposed to predict gas concentrations, volumes of gases released and fed into the breathing simulator at a certain time interval. Furthermore, it is necessary to ensure accurate reproduction of the volumes of released GAM and nitrogen and carbon dioxide fed on each cycle breaths. If inaccurate data on the volumes are reproduced, the accumulated errors lead to inadequate simulation of oxygen consumption and reduce the quality of the SCBA tests.

The purpose of this work is to formulate the problem of optimal control of the AL facility and develop an algorithm of AL actuators control to reduce the number of reproduction errors in the given volumes of gases.

II. THE STRUCTURE AND WORKING PRINCIPLE OF THE PREDICTIVE CONTROL SYSTEM

Fig. 1 shows a simplified block diagram of the control system of the "Artificial Lungs" facility. The principle of operation of the control system is considered as follows.

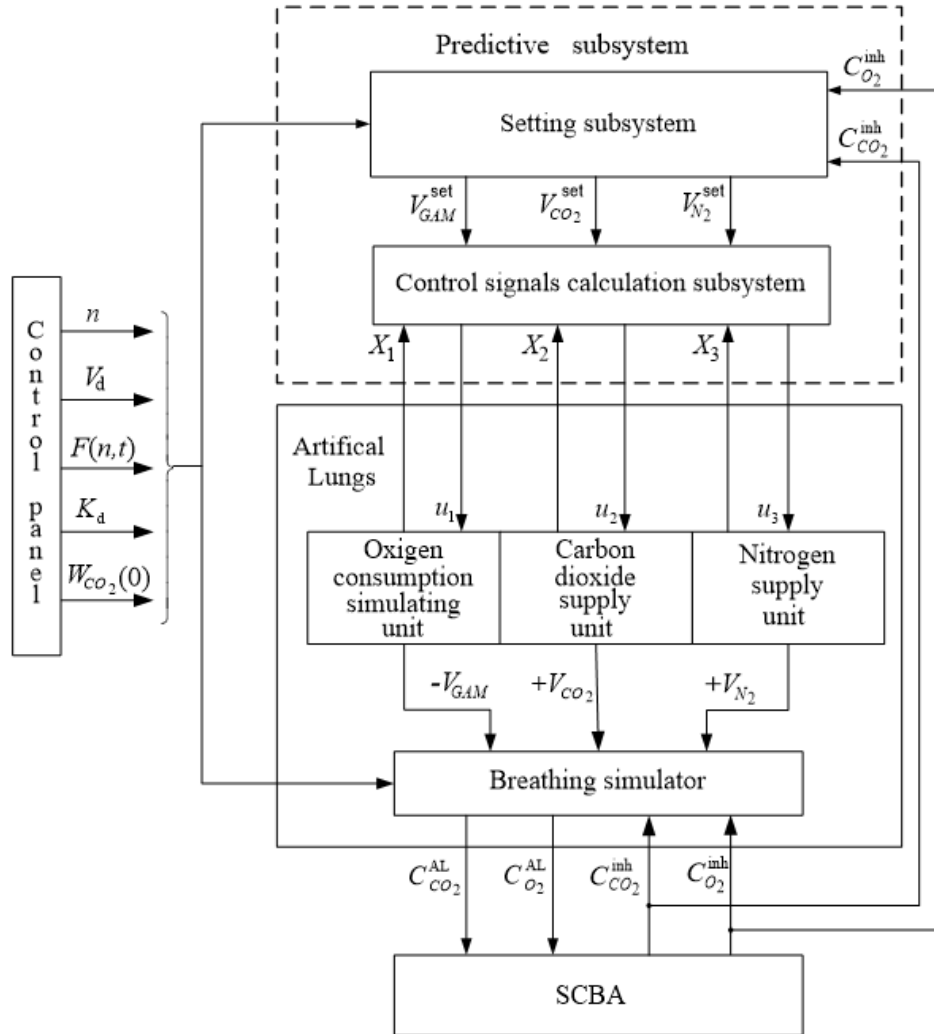


Fig. 1. The block diagram of the control system of Artificial Lungs facility

The operator sets the SCBA test mode in the AL facility from the control panel and sets frequency n , depth V_d breathing factor K_d , the type of pneumotachogram $F(n,t)$ and carbon dioxide flow $W_{CO_2}(0)$, imitating CO_2 emissions by a human being, fed into the breathing simulator.

A. Setting subsystem

The process of operation of the system is divided into cycles. At each cycle, the necessary volumes of released GAM discharge and fed CO_2 and N_2 are corrected and prediction of the system status for a certain period of time corresponding to the next inhalation is made.

On the basis of a predetermined test mode and measured values of exhaled gas concentrations $C_{CO_2}^{inh}$ and $C_{O_2}^{inh}$, the setting

subsystem forms the preset values of released GAM $V_{GAM}^{set}(t)$ and fed gases $V_{CO_2}^{set}(t)$, $V_{N_2}^{set}(t)$ in the time function. The predictive model of the setting subsystem is determined by the system of equations (1):

$$\left. \begin{aligned} \frac{dV_{GAM}(t)}{dt} &= W_{GAM} F(n,t), \quad V_{GAM}(t_{sc}) = 0; \\ \frac{dV_{CO_2}(t)}{dt} &= (W_{CO_2} + W_{CO_2}(0)) F(n,t), \quad V_{CO_2}(t_{sc}) = 0; \\ \frac{dV_{N_2}(t)}{dt} &= W_{N_2} F(n,t), \quad V_{N_2}(t_{sc}) = 0, \end{aligned} \right\} \quad (1)$$

where

$W_{GAM} = W_{CO_2}(0)/(K_d C_{O_2}^{inh})$ is the flow of released GAM on inhalation;

$W_{CO_2} = C_{CO_2}^{inh} W_{GAM}$ is the flow of additional supply of CO_2 on inhalation from the buffer tank;

$W_{N_2} = (1 - C_{O_2}^{inh} - C_{CO_2}^{inh}) W_{GAM}$ is the supply flow of N_2 on inhalation from the buffer tank;

$F(n, t)$ is the function, determining the type of breathing pneumotachogram;

t_{sc} is the time of the start of another inhalation-exhalation cycle.

Integrating system (1) in the interval of $[t_{sc}, t_{sc} + t_{it}]$, where t_{it} is the inhalation time, the preset values of volumes of released and fed gases in the function of time are obtained:

$$V_{GAM}^{set}(t), V_{CO_2}^{set}(t), V_{N_2}^{set}(t), t \in [t_{sc}, t_{sc} + t_{it}].$$

These preset values of volumes of gases, and current state vector $[X_1, X_2, X_3]^T$ are used by the subsystem to calculate control signals u_1, u_2, u_3 for direct control of actuators, simulating oxygen consumption (GAM release), and supply of carbon dioxide and nitrogen, respectively.

B. A control algorithm with a predictive model

For the construction of control algorithms for actuators that minimize reproduction errors in given volumes of gases, the method of analytical design of optimal controllers by the A.A. Krasovsky's criterion of generalized operation [5 - 14] is used.

Based on this method, the optimal control algorithms for nonlinear dynamic objects that can operate in real time are developed. A predictive algorithm on a sliding range of optimization with calculation of sensitivity matrix [9] is used. Let the mathematical model of the control object is described by the differential equations:

$$dx/dt = f(x, y, t), \quad dy/dt = u, \quad x(0) = x_0, \quad y(0) = y_0, \quad (2)$$

where

x is the state vector of the control object;

f is the differentiable in all arguments nonlinear vector function;

y is the position vector of steering bodies;

u is the rate of change y (control).

In model (2), control is performed by changing the rate of influences y ; a $x = x(y, t)$ is a composite function.

It is necessary to find the control that minimizes the functional of the generalized operation on a sliding range ($t_u, t_u + T$):

$$I = \int_{t_u}^{t_u+T} Q(x, y, \tau) d\tau + \frac{1}{2} \int_{t_u}^{t_u+T} (u^T K^{-1} u + u_{opt}^T K^{-1} u_{opt}) d\tau \quad (3)$$

where

Q is the scalar function differentiable by its arguments, and characterizing the quality of the control process on the interval ($t_u, t_u + T$);

K is the diagonal matrix of coefficients of control effectiveness;

u_{opt} is the optimal rate of change y (optimal control);

t_u is the moment determining control influences;

T is the prediction interval.

According to [6, 9, 10], control u_{opt} is calculated as follows:

$$u_{opt}(t_u) = -K \frac{\partial S(t_u)}{\partial y(t_u)} \quad (4)$$

where $S(t)$ is the solution of the Lyapunov equation:

$$\frac{\partial S}{\partial t} + \frac{\partial S}{\partial x} f(x_f, t) = -Q(x_f, t), \quad S(t_u + T) = 0, \quad (5)$$

at free motion of object (2) on the interval of ($t_u, t_u + T$):

$$dx_f/dt = f(x_f, y, t), \quad dy/dt = 0. \quad (6)$$

On free movement (6) left side (5) is transformed into a full derivative by t :

$$\dot{S} = -Q(x_f, t), \quad S(t + T) = 0. \quad (7)$$

Differentiating (7) with respect to y according to the rule of differentiating a composite function, the formula is obtained [9]:

$$\frac{d}{dt} \left(\frac{\partial S(t_u)}{\partial y(t_u)} \right) = - \frac{\partial Q(t)}{\partial x_f} \cdot \frac{\partial x_f(t)}{\partial y(t_u)} - \frac{\partial Q(t)}{\partial y(t_u)}, \quad (8)$$

$$\frac{\partial x_f(t)}{\partial y(t_u)} = Z(t)$$

where $Z(t)$ is a sensitivity matrix of the solution of equation (6) for parameter vector y , satisfying the sensitivity equation:

$$\dot{Z}(t) = \frac{\partial f(x_f, y, t)}{\partial x_f(t)} Z(t) + \frac{\partial f(x_f, y, t)}{\partial y(t_u)} \quad (9)$$

with the initial condition:

$$Z(t_u) = 0, \quad (10)$$

where Jacobi matrices $\frac{\partial f(x_f, y, t)}{\partial x_f(t)}, \frac{\partial f(x_f, y, t)}{\partial y(t_u)}$ are calculated for $x_f(t)$.

A block diagram of the control algorithm is shown in Fig. 2.

Functioning of the algorithm is as follows. At each correction cycle, the information on the state variables of the control object (the signals from the meters) is entered into the

estimation system, which estimates the vector of the system status (noise filtering, and coordinate restoration of vector x , which cannot be measured). Estimates of state vector \hat{x}, \hat{y} are entered into the predictive model.

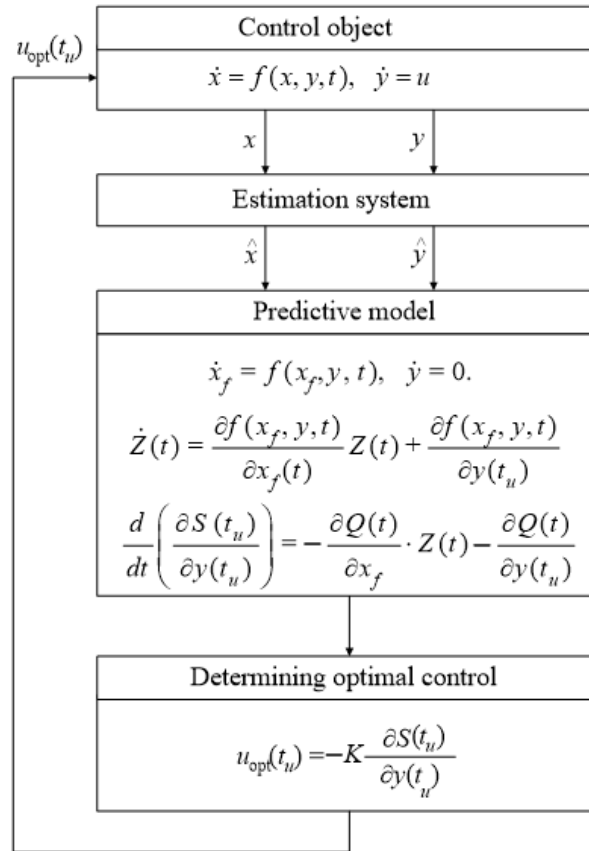


Fig. 2. A block diagram of the control algorithm

Control signals for object (2) calculated by formula (4) at time points t_u at intervals Δt_c , where Δt_c is a correction control cycle. Optimal equation $u_{opt}(t_u)$ is calculated at each cycle by integration of predictive model equations (6) and (8) and (9) on interval $(t_u, t_u + T)$.

C. Statement of the problem and the implementation of the algorithm of optimal control of actuators

The statement of the optimal control problem and the implementation of the algorithm for calculating the subsystem of control signals u_1, u_2, u_3 is considered as follows. Let the estimation system (it is not considered in this example,) provides an accurate estimate of state vector $[X_1, X_2, X_3]^T$ (see below), noise of sensors (not shown in Fig. 1) are absent. The equation, realizing the proposed algorithm, is formed as follows.

Let the mathematical model of control object in accordance with (2) have the form:

$$\left. \begin{aligned} \frac{dV_i}{dt} &= S_{pi} g_i, \quad V_i(t_u) = 0, \quad 0 \leq V_i \leq V_i^{\max}; \\ \frac{d\vartheta_i}{dt} &= \frac{1}{T_{di}} (-\vartheta_i + k_{di} \mu_{icon}), \quad \vartheta_i(t_u) = 0, \quad |\vartheta_i| \leq \vartheta_i^{\max}; \\ \frac{d\mu_{icon}}{dt} &= u_i, \quad i = 1, 2, 3; \end{aligned} \right\} \quad (11)$$

where

$V_1 = V_{GAM}(t)$ is the GAM volume removed from the system in the inhalation phase;

$V_2 = V_{CO2}(t)$, $V_3 = V_{N2}(t)$, are volumes of carbon dioxide and nitrogen, fed to the system at the inhalation phase;

$\vartheta_1, \vartheta_2, \vartheta_3$ are velocities of linear rods of the units simulating oxygen consumption and supply of carbon dioxide and nitrogen;

$\mu_{1con}, \mu_{2con}, \mu_{3con}$ are control signals in the respective channels;

u_1, u_2, u_3 are rates of change of control signals (control);

S_{p1}, S_{p2}, S_{p3} are areas of pistons of reciprocating feeders of GAM, CO_2 and N_2 , respectively;

$T_{di}, k_{di}, (i=1, 2, 3)$ are parameters of drive models.

The quality control criteria to be minimized for the object (11) will take the form:

$$I = \frac{1}{2} \int_{t_u}^{t_u+T} \sum_{i=1}^3 [\alpha_i (V_i - V_i^{\text{set}})^2 + \beta_i (\dot{V}_i)^2 + Q_i^f] d\tau + \frac{1}{2} \int_{t_u}^{t_u+T} \sum_{i=1}^3 (k_i^{-1} u_i^2 + k_i^{-1} u_{i\text{opt}}^2) d\tau \quad (12)$$

where α_i, β_i are weighting factors (positive), which can be varied to achieve the predetermined quality of the transition process;

$Q_i^f = Q_{li}^f + Q_{2i}^f$ is a penalty function,

$$Q_{li}^f = \begin{cases} 0 & \text{if } V_i \leq V_i^{\text{max}}, \\ \gamma_i (V_i - V_i^{\text{max}})^2 & \text{if } V_i > V_i^{\text{max}}, \end{cases}$$

$$Q_{2i}^f = \begin{cases} 0 & \text{if } |\mathcal{G}_i| \leq \mathcal{G}_i^{\text{max}}, \\ \eta_i (\mathcal{G}_i - \mathcal{G}_i^{\text{max}})^2 & \text{if } |\mathcal{G}_i| > \mathcal{G}_i^{\text{max}}, \end{cases}$$

γ_i, η_i are parameters (positive coefficients) of the penalty function defining "rigor" of the predetermined boundary;

In accordance with the notation of II.B, we have:

$x = [X_1, X_2, X_3]^T = [V_{\text{GAM}}, \mathcal{G}_1, V_{\text{CO}_2}, \mathcal{G}_2, V_{\text{N}_2}, \mathcal{G}_3]^T$ is the state vector of control object;

$y = [\mu_{1\text{con}}, \mu_{2\text{con}}, \mu_{3\text{con}}]^T$ is the position vector of steering bodies;

$u = [u_1, u_2, u_3]^T$ – control vector (rate of change of y);

$Q(x, y, t) = \sum_{i=1}^3 [\alpha_i (V_i - V_i^{\text{set}})^2 + \beta_i (\dot{V}_i)^2 + Q_i^f]$ – function characterizing the desired quality of the control process on interval (t_u, t_u+T) ;

$K = \text{diag}[k_i]$ – matrix of coefficients of control efficiency.

Then, following the procedure of formation of the optimal control algorithm (see II.B), we obtain the implementation of this algorithm by actuators.

Optimal controls of type (4) are determined by the expression:

$$u_{i\text{opt}}(t_u) = -k_i \frac{\partial S(t_u)}{\partial \mu_{i\text{con}}(t_u)}, \quad i = 1, 2, 3. \quad (13)$$

The predictive model consists of:

- equations in the form of free movement of the object (6):

$$\left. \begin{aligned} \frac{dV_i}{dt} &= S_{pi} \mathcal{G}_i; \\ \frac{d\mathcal{G}_i}{dt} &= \frac{1}{T_{di}} (-\mathcal{G}_i + k_{di} \mu_{i\text{con}}); \\ \frac{d\mu_{i\text{con}}}{dt} &= 0, \quad i = 1, 2, 3; \end{aligned} \right\} \quad (14)$$

- the equations of sensitivity of type (9):

$$\left. \begin{aligned} \frac{dZ_{i1}}{d\tau} &= S_{pi} Z_{i2}; \\ \frac{dZ_{i2}}{d\tau} &= -\frac{1}{T_{di}} Z_{i2} + \frac{k_{di}}{T_{di}}, \quad i = 1, 2, 3, \end{aligned} \right\} \quad (15)$$

where $Z_{i1} = \frac{\partial V_i}{\partial \mu_{i\text{con}}}, Z_{i2} = \frac{\partial \mathcal{G}_i}{\partial \mu_{i\text{con}}}$ are sensitivity functions,

- the equations for the partial derivative of the Lyapunov function of form (8):

$$\left. \begin{aligned} \frac{d}{dt} \left(\frac{\partial S}{\partial \mu_{i\text{con}}} \right) &= -[\alpha_i (V_i - V_i^{\text{set}}) + \gamma_i (V_i - V_i^{\text{max}})] Z_{i1} - \\ &\quad - [\beta_i \dot{V}_i S_{pi} + \eta_i (\mathcal{G}_i - \mathcal{G}_i^{\text{max}})] Z_{i2}, \\ \gamma_i &= 0 \quad \text{if } V_i \leq V_i^{\text{max}}; \\ \eta_i &= 0 \quad \text{if } |\mathcal{G}_i| \leq \mathcal{G}_i^{\text{max}}, \quad i = 1, 2, 3. \end{aligned} \right\} \quad (16)$$

Equations (15) and (16) are integrated on interval (t_u, t_u+T) under zero initial conditions, and system (14) is integrated with the initial conditions corresponding to the current state of object (11) at the end of previous cycle Δt_c of control correction.

III. CONCLUSION

The structure of the predictive control system for the "Artificial Lungs" facility, which consists of setting and control subsystems, is considered. We proposed an algorithm for the operation of the setting subsystem. We formalized the task of optimal control for AL facility and proposed the implementation of an optimal control algorithm for the subsystem of control signals by actuators, simulating oxygen consumption, supply of carbon dioxide and nitrogen, respectively.

Functioning of the control system is as follows. At each inhalation cycle on interval $[t_{sc}, t_{sc}+t_{it}]$, the system of equations (1) is integrated, for example, by the method of [15], and functions $V_{\text{GAM}}^{\text{set}}(t), V_{\text{CO}_2}^{\text{set}}(t), V_{\text{N}_2}^{\text{set}}(t)$ are calculated. These functions are entered into the subsystem for calculation of control signals. The algorithm of optimal control is used. At each cycle of correction control in the segment $[t_u, t_u+T]$ (t_u is current time of controls calculation, T is prediction interval), an integration of the equations of the predictive model (14-16) is carried out periodically with interval Δt_c , and optimal controls by actuators using formula (13) are calculated. By

appropriate selection of controls correction cycle Δt_c , prediction interval T , weighting factors α_i , β_i , parameters γ_i , η_i , one can ensure the desired quality of transient processes in the system.

Thus, the proposed algorithm can be used to control the gas volume in the AL facility with a given accuracy and minimal energy control costs.

Acknowledgment

This article was supported by the Russian Science Foundation (Agreement No. 15-19-10028).

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