

Analysis of alternative controller structures for modeling and controlling a multi-channel water plant

Askhat Asset
Al-Farabi Kazakh National University
Department of Information Technology
Almaty, Kazakhstan
asset.askhat.81@gmail.com
ORCID: 0009-0005-8842-328X

Vadim Zhmud
Al-Farabi Kazakh National University
Department of Information Technology
Almaty, Kazakhstan
vadim.zhmud@kaznu.kz
ORCID: 0000-0002-1708-9211

Madina Mansurova
Al-Farabi Kazakh National University
Department of Information Technology
Almaty, Kazakhstan
madina.mansurova@kaznu.kz
ORCID: 0000-0002-9680-2758

Nurlan Sarsenbayev
Satbayev University
Department of Automation and Control
Almaty, Kazakhstan
n_sarsenbayev@satbayev.university
ORCID: 0000-0001-8640-7175

Gulmira Bayandina
Satbayev University
Department of Automation and Control
Almaty, Kazakhstan
g_bayandina@Satbayev.University
ORCID: 0000-0003-0339-1986

Gulbagila Kuandikova
Satbayev University
Department of Automation and Control
Almaty, Kazakhstan
kuandikova75@gmail.com
ORCID: 0000-0002-5398-5494

Abstract. The task of controlling multi-channel objects, that is, objects with many inputs and many outputs, MIMO, can be the most effectively solved by a multi-channel controller that has the same number of inputs and outputs as the controlled object has. We consider only multichannel controllers that have the same number of inputs and outputs. Traditionally, in the matrix of such a controller, each element is a scalar PID controller, that is, a controller containing proportional, integrating and derivative channels. In this case, an $n \times n$ object requires n^2 scalar PID controllers, each with three channels. The calculation of such a controller requires the calculation of $3n^2$ parameters.

Keywords. Controllers, PID, MIMO, optimization, modeling, simulation

Introduction

It is known that in order to control a multichannel object, i.e. an object with n inputs and n outputs, also called MIMO objects, (many inputs - many outputs), controllers of the same dimension, $n \times n$, can be most successfully used [1]. There are well-known attempts to control objects in which the number of inputs does not match the number of outputs [2]. All of them should be divided into two types: a) objects in which the number of inputs is greater than the number of outputs, b) objects in which the number of inputs is less than the number of outputs [3].

If we consider cold and hot water of the water supply system as an object of research, recall that these two options should be considered from different positions, namely: if the number of inputs is greater than the number of outputs of the object, then this is not a problem, but an additional opportunity for managing the object. For this case, there are methods for the effective use of additional inputs; in this direction, science can successfully develop, if researchers do not ignore already known results[4]. For the case where the number of outputs exceeds the number of inputs, it should be recognized that the excess outputs could not be controlled.

There is an erroneous terminology when the authors believe that if the output signals at additional outputs somehow depend on the input signals arriving at the object,

then, therefore, this can also be considered as control. Another mistake is that if in some way, under some specific initial conditions, it is possible to reduce the output signals at the extra outputs to zero or to a constant level, this can also be considered control. Both are erroneous, which is shown in detail in the publication [5].

If the goal of control is, for example, stabilization of the rotation speed, then the angle of rotation as a result of such control should change according to a linear law, increase linearly or decrease linearly (i.e., rotate in the opposite direction). If the rotation angle is stabilized, then the rotation speed should become equal to zero because of control. Therefore, in both cases, as in all similar cases, the requirements for the value of the output quantity from among the “main” output signals impose certain requirements on the “additional” output signals. These two signals are interrelated. In fact, to form a control problem, it is enough to make requirements only for the main output values of the object, the requirements for additional values are formed automatically. Accordingly, when controlling such an object, it is enough to ensure the requirements for the “basic” output values, and then the requirements for the “additional” output values will be fulfilled automatically. For this reason, additional outputs should not be considered, except as an additional opportunity to receive additional signals for organizing, for example, local feedbacks [6].

In view of the foregoing, we do not consider the problems of controlling objects in which the number of inputs does not coincide with the number of outputs. The range of tasks includes only the control of objects of dimension $n \times n$. The demonstration of the proposed approaches was carried out by the method of numerical optimization on the example of an object with a dimension of 2×2 .

It is known that to control an $n \times n$ object, a controller of the same dimension is required. As a rule, two variants of such controllers are considered: a) complete controllers, in which from each input there is a separate single-channel controller for each output, there are $n \times n = n^2$ such single-channel controllers in a similar controller; b) diagonal

controllers, in which non-zero single-channel controllers are located only in the main diagonal of the matrix transfer function of the controller, the total number of which is n . The case of a diagonal regulator is a set of n single-channel regulators, one regulator for each channel. Obviously, the diagonal regulator is much simpler and less capable. It is also obvious that the full regulator is more complex and has more options, if only for the reason that the diagonal regulator is just a special case of it. This paper proposes a structure that occupies an intermediate position between a full controller and a diagonal controller. This idea is demonstrated on the example of a two-channel object, i.e. a 2×2 object. The full controller must contain four PID controllers, the diagonal controller consists of only three PID controllers, while the proposed controller contains three PID controllers, with which it can be called a three-element regulator[7].

The article defines the height of the rotation axis of the round gate with water level adjustment, as well as an analysis of the upper level of the water flow, a regulator for regulating the flow of water is used in the middle and final part of the water supply network, the use of such a regulator for drainage, wells and culverts is envisaged, this regulator is designed to reduce water consumption [8]. The possibility of obtaining information in real time in the hydrodynamic process in water supply systems is considered, a regulator is provided to maintain pressure in the water supply network in a constant mode and modern technology of remote control and control of water is applied, the method of mathematical hydraulic modeling for water supply systems is applied [9]. According to the 365-day period for managing the water supply system in the city, the model is built in an SVM environment taking into account seasonal and daily meteorological variability, at the same time, a reliable statistical methodology for modeling water demand in cities for 365 days by average per capita consumption has been developed to solve the problem of daily water demand with similar indicators. In the article, according to studies conducted over the past decade, coagulation-flocculation, improvement of membrane filtration processes by adsorption is provided, as well as other heavy metals and the impact of new pollutants on human health are analyzed, various technologies that positively affect consumption and daily activities, especially high-quality water supply to rural residents are studied and analyzed. The analysis of the process in the field of artificial intelligence and blockchain for effective management of water resources under climate change is carried out, it shows how climate leads to changes in large-scale availability of water, water resources management, blockchain data securitization protocols, regulators combined with artificial intelligence algorithms trained by remote water sensors were used for water distribution. In this article, an effective mathematical model of an automatic latch for regulating the water level with a high flow rate has been created, used for the automatic gate control system used to ensure free flow through the gate, regulates the level at the inlet of the water pipe located near the control level, such a model is very effective for modeling the hydraulic process [10].

1 Theory

A linear object with dimensions $n \times n$ can be described by a matrix transfer function in the Laplace transform domain:

$$W(s) = \begin{bmatrix} w_{11}(s) & \dots & w_{n1}(s) \\ \dots & \dots & \dots \\ w_{1n}(s) & \dots & w_{nn}(s) \end{bmatrix} \quad (1)$$

Here s is the argument of the Laplace transform, $w_{ij}(s)$ are the scalar transfer functions of the individual elements of the matrix (1). In particular, for a second-order linear object, these scalar transfer functions have the following form:

$$w_{ij}(s) = \frac{k_{ij}}{1 + T_{ij1}s + T_{ij2}s^2} \quad (2)$$

Here k_{ij} , T_{ij1} , T_{ij2} are coefficients.
The object equation in this case looks like this:

$$X(s) = W(s)U(s) \quad (3)$$

Here $X(s)$ is the column vector of object output values (signals), $U(s)$ is the column vector of object input signals:

$$X(s) = \begin{bmatrix} x_1(s) \\ \dots \\ x_n(s) \end{bmatrix} \quad (4)$$

$$U(s) = \begin{bmatrix} u_1(s) \\ \dots \\ u_n(s) \end{bmatrix} \quad (5)$$

The equation of the system with the controller will have the following form:

$$U(s) = W_R(s)[V(s) - X(s)] \quad (6)$$

Here $V(s)$ is a column vector of assignments, i.e. prescribed values for the column vector of output signals, $W_R(s)$ is the matrix transfer function of the controller.

$$W_R(s) = \begin{bmatrix} w_{11}(s) & \dots & w_{n1}(s) \\ \dots & \dots & \dots \\ w_{1n}(s) & \dots & w_{nn}(s) \end{bmatrix} \quad (7)$$

An object is considered to be controlled by system (6), (7) if the individual elements of the column vector $V(s)$ can be set independently of each other. This is the fundamental difference from the pseudoscientific approach, in which dependent quantities are erroneously interpreted as additional output signals.

A complete controller is a controller in which all elements of the matrix (7) are nonzero. The best known and usually the most effective is the controller containing PID controllers as elements, i.e. elements described by the following relation:

$$w_{ijr}(s) = K_{ijP} + \frac{K_{ijI}}{s} + K_{ijD}s \quad (8)$$

In a diagonal controller, all elements except those in which $i = j$ are equal to zero.

$$w_{ijr}(s) = \begin{cases} K_{ijP} + \frac{K_{ijI}}{s} + K_{ijD}s & \forall i \neq j \\ 0 & \forall i = j \end{cases} \quad (9)$$

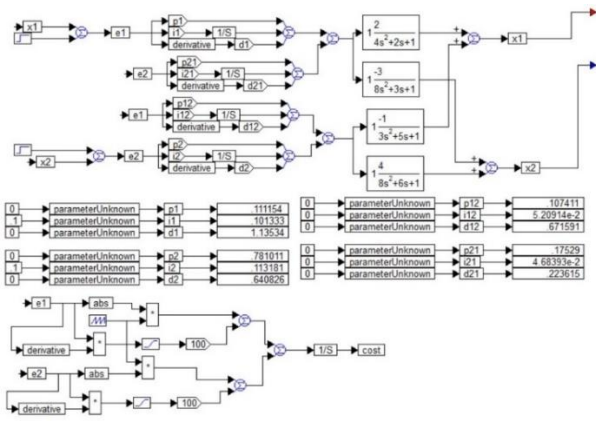


Fig. 1. System model for numerical optimization of a four-component controller for a linear plant with a dimension of 2×2



Fig. 2. Transient process in a system with a four-component regulator: 1 - output x_1 , 2 - output x_2

Figure 3 shows a block diagram for modeling a system with a diagonal regulator, and Figure 4 gives the result in the form of transient processes in the system. The resulting controller looks like this:

$$W_R(s) = \begin{bmatrix} 0.1839 + \frac{0.147}{s} + 0.5558s & 0 \\ 0 & 1.512 + \frac{0.6305}{s} + 1.944s \end{bmatrix} \quad (10)$$

The obtained transient processes are worse than in the case of using a full regulator. Figure 4 shows that there is no overshoot in the first channel, but there is a spurious response to the signal jump at the second input, the value of which is 30%. The second channel has a 10% overshoot, as well as a spurious response to the signal jump at the second input of 15%. The lifetime of a significant error is about 20 s.

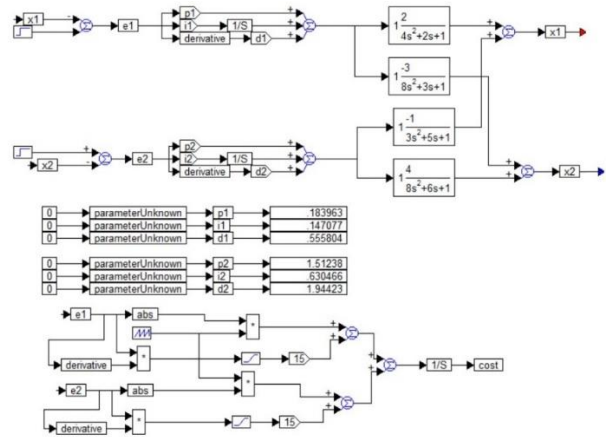


Fig. 3. System model for numerical optimization of a two-component controller for a 2×2 linear plant, the best value of the coefficients in the cost function

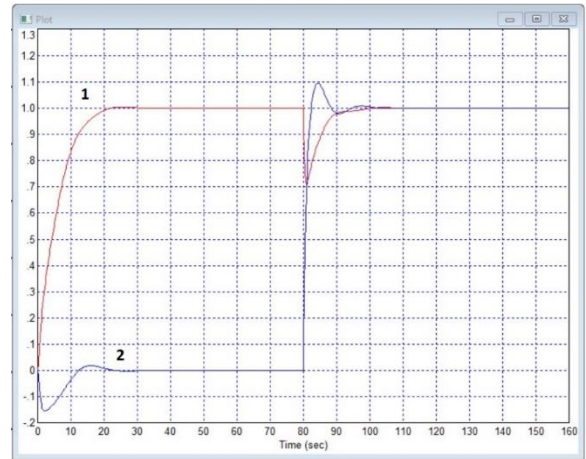


Fig. 4. Transient process in a system with a regulator according to Fig. 3

2 Results of solving the problem with the proposed controller structure

Figure 5 shows a block diagram of the project for solving the problem by the proposed method using a three-element controller with a dimension of 2×2 . At the same time, the cost function is used the same, it depends only on two main errors in the two initial control channels of the object.

The resulting controller coefficients are shown in the windows of the respective displays. Thus, the controller with the following parameters is calculated:

$$w_+(s) = 0.4484 + \frac{0.79}{s} + 5.42s \quad (11)$$

By relation (11), one can easily recalculate the transfer function (11) to the form of a full controller, but, as can be seen from the structure in Fig. 5, the structure can be implemented in a simpler way, in which instead of four PID controllers, there are only three, as well as several additional totalizers. The solution of this problem in this form was much simpler than the solution of the problem of finding a complete controller, since it was required to find by the numerical optimization method not 12 coefficients, but only 9.

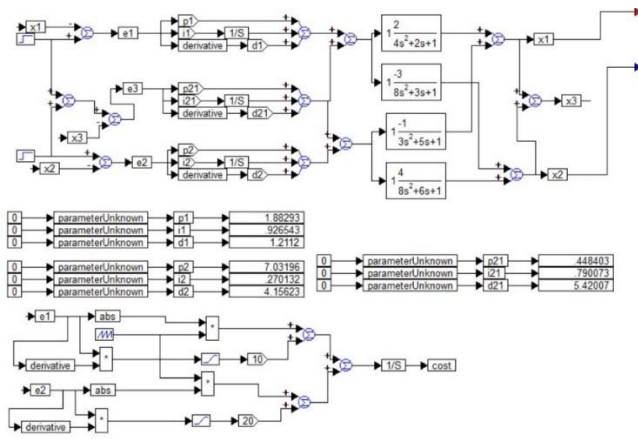


Fig. 5. System model for numerical optimization of a three-component controller for a 2×2 linear plant, the coefficients in the cost function do not match (10 and 20, respectively)

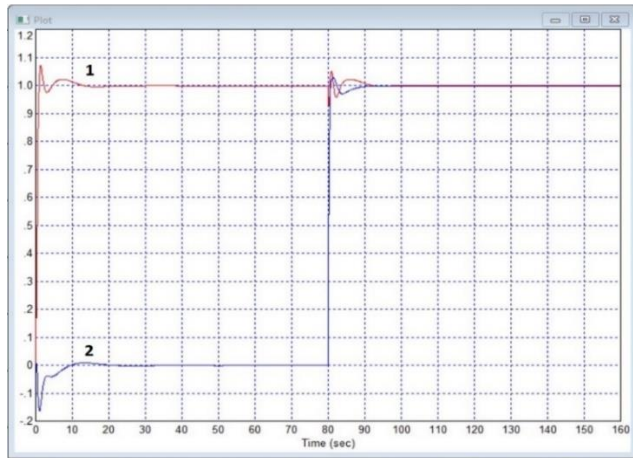


Fig. 6. Transient process in a system with a regulator according to Fig. 5

Discussion and Conclusions

This paper proposes a controller structure for a two-channel plant that is simpler than a full controller but more complex than a diagonal controller is. In terms of efficiency, such a structure has demonstrated advantages over both known structures in at least one example. Without detailed further research, it cannot be argued that the advantages of this structure will always take place; however, it has a right to exist. Apparently, the proposed method can be extended to control problems for multichannel objects with a large number of channels, where the number of parameters that require calculation increases according to a power law with an increase in the number of channels, it is relevant, if we consider an alternative structure of the regulator for managing a multi-channel water supply facility.

Literature

- 1) RS Soman, F. Gopmandal and A. Ghosh, "MIMO PID compensation for dynamic positioning of a ship," *2018 Indian Control Conference (ICC)*, Kanpur, India, 2018, pp. 137-142, doi: 10.1109/INDIANCC.2018.8307967. <https://ieeexplore.ieee.org/document/8307967>

- 2) L. Ilyas, E. Ahmed and S. Nacer, "PID Controller of a MIMO system using Ant Colony Algorithm and its application to a poultry house system," *2019 5th International Conference on Optimization and Applications (ICOA)*, Kenitra, Morocco, 2019, pp. 1-7, doi: 10.1109/ICOA.2019.8727710. <https://ieeexplore.ieee.org/document/8727710>
- 3) Guardño, R.; Lopez, MJ; Sánchez, VM MIMO PID Controller Tuning Method for Quadrotor Based on LQR/LQG Theory. *Robotics* 2019, 8, 36. <https://doi.org/10.3390/robotics8020036>
- 4) Krokavec, D.; Filasová, A. On PID Design Constraints in Relation to Control of Strictly Metzler Linear MIMO Systems. *Symmetry* 2021, 13, 1589. <https://doi.org/10.3390/sym13091589>
- 5) Peretz, Y. A Randomized Algorithm for Optimal PID Controllers. *Algorithms* 2018, 11, 81. <https://doi.org/10.3390/a11060081>
- 6) Bouhabza, K.; Guatni, M.; Bouzid, Y.; Hamerlain, M. ACO-Based Optimal MIMO Sliding Mode Controller Design for a New Reconfigurable Unmanned Aerial Vehicle. *Eng. Proc.* 2023, 29, 9. <https://doi.org/10.3390/engproc2023029009>
- 7) Cruz-Díaz, C.; del Muro-Cuellar, B.; Duchén-Sánchez, G.; Marquez-Rubio, JF; Velasco-Villa, M. Observer-Based PID Control Strategy for the Stabilization of Delayed High Order Systems with up to Three Unstable Poles. *Mathematics* 2022, 10, 1399. <https://doi.org/10.3390/math10091399>
- 8) Askhat Asset, Madina Mansurova, Vadim Zhmud "The Use of a Digital Double for Effective Control of an Object with Many Destabilizing Nonlinear Feedbacks", *Digital Technologies in Education, Science and Industry 2022, Proceedings of the 7th International Conference on Digital Technologies in Education, Science and Industry (DTESI 2022)* International Information Technology University Almaty, Kazakhstan, 3-10pp. October 20-21, 2022.
- 9) Expert System for Assessing the Efficiency of Information Security, Askhat Asset, Aizhan Erulanova, Gulzhan Soltan, Aizhan Baidildina, Marzhan Amangeldina *Proceedings of 2020 7th International Conference on Electrical and Electronics 355-359pp. Engineering (ICEEE 2020)* April 14-16, 2020, Antalya, Turkey.
- 10) Askhat Asset, Madina Mansurova, Vadim Zhmud "The Use of a Digital Double for Effective Control of an Object with Many Destabilizing Nonlinear Feedbacks", *Digital Technologies in Education, Science and Industry 2022, Proceedings of the 7th International Conference on Digital Technologies in Education, Science and Industry (DTESI 2022)* International Information Technology University Almaty, Kazakhstan, 3-10pp. October 20-21, 2022.