IMPROVEMENT OF OBJECT CONTROL BASED ON INTERNET OF THINGS TECHNOLOGY UNDER VARIABLE DELAYS IN THE CONTROL NETWORK

The study focuses on distributed control systems managing objects affected by varying and unpredictable delays, both in terrestrial and space applications. It examines how these delays impact the stability and accuracy of remote control systems, especially in environments with variable transmission times. The main issue addressed is instability caused by variable delays in IoT-based control systems, which affect both terrestrial systems (such as smart homes and industrial automation) and space missions (such as controlling space objects from Earth). The challenge is ensuring stable and accurate control despite unpredictable delays in communication channels.

A new control system design is proposed, incorporating a unique controller structure with a bypass channel to ensure stability under variable delays. The system was validated through mathematical modeling, showing a maximum overshoot of 3% in the PID configuration and near elimination of overshoot with the bypass channel. It outperforms traditional methods like the Smith predictor, which fails when delays deviate by as little as 1–3%. The proposed system ensures stable and accurate control in both terrestrial IoT applications, effectively handling unpredictable delays and maintaining performance in real-time environments

Keywords: Internet of Things, PID-regulators, control, controllers, negative feedback, non-stationary objects, time delay, space systems

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1. Introduction

The relevance of the study in the field of Internet of Things (IoT) object management under conditions of variable network delays is driven by the rapid development of technologies and the emergence of new complex challenges in automation and remote control [1]. The active growth of global communication networks and the widespread adoption of IoT devices create a sustained demand for reliable remote monitoring and control systems, encompassing sensors, actuators, and complex cyber-physical systems [2].

Unlike classical control systems with predictable dynamics, IoT systems operate in an environment with non-deterministic network characteristics. The key challenges here are variable data transmission delays (uncertain and time-varying) and potential packet loss [3, 4]. These factors directly threaten the stability, performance, and ultimately, the security of systems, as evidenced by the analysis of modern industrial and infrastructure IoT applications [5]. Therefore, the development of new algorithmic and architectural solutions robust to network imperfections represents a significant scientific and practical problem [6].

The proliferation of the Internet of Things (IoT) has enabled remote control capabilities across global networks. However, this paradigm introduces a fundamental challenge: control and feedback packets traverse complex network paths, suffering from variable time delays and potential losses [7]. As IoT systems become integral to diverse sectors, including education which fosters digital literacy in these technologies [8], the need for reliable control becomes paramount. This reality renders traditional compensation methods, like the classical Smith predictor, inadequate due to their

lack of robustness against such network-induced uncertainties and variations in the plant dynamics. Consequently, the design of control algorithms must evolve to explicitly account for these non-ideal network characteristics.

Various approaches are proposed in the literature for compensating variable delays in networked control systems. For example, Choi and Krstic consider the compensation of time-varying input delays for nonlinear discrete systems, offering algorithms that ensure stability within a known range of varying delays [9]. These methods are particularly relevant in applications where the delay depends on the network conditions (e.g., in IoT or when controlling unmanned vehicles), as they allow for the adaptation of the control algorithm to the current level of network delays.

However, in some applications, it may be necessary to close the feedback signal directly through the control device. This should generally be avoided whenever possible; however, for instance, in the real-time control of an unmanned vehicle whether ground-based, surface, or aerial the feedback loop may be closed through a human operator. This is because control decisions need to be made based on video information received and analyzed at the control center. If a human operator is present in the feedback loop, the system is referred to as automated, and in this case, the operator's reaction speed to changing conditions largely determines the accuracy and responsiveness of the control. If the operator does not act within the loop and is present only as a supervisor who sets the prescribed task without comparing the instruction to the actual position of the object or generating specific control signals for the actuator based on this then the system is called automatic, not automated. In such a system, the response speed can be significantly higher than the operator's reaction time; however, it is limited by the delay associated with the transmission of the signal from the control center to the object and back. This transport delay may vary depending on the object's distance, making the control problem particularly relevant when the delay in its mathematical model is not stationary but can change within certain limits. These limits can be estimated in advance by knowing the maximum distance of the object from the control center.

Thus, it can be concluded that the problem of controlling an object with variable delay is becoming increasingly relevant, partly due to the development of Internet of Things technology.

2. Literature review and problem statement

The problem of controlling objects with significant delays in the feedback loop has been widely discussed in the context of distributed control systems, especially as technologies evolve and new challenges emerge in automation and remote control. The classical methods of delay compensation, such as the Smith predictor, have proven effective in certain scenarios, where the delay is known and remains constant. For instance, in [10, 11], it is shown that the Smith predictor works well when delays are predictable and constant, providing an efficient solution for systems where delay characteristics are well-understood. However, as the field advances, particularly in IoT applications, variable and unpredictable delays have become more common, posing new challenges that these traditional methods cannot always address.

The primary difficulty arises from the non-stationary nature of delays, which depend on external factors such as network conditions. In IoT systems, for example, data transmission delays are uncertain and time-varying, which threatens the stability and performance of control systems [7, 9]. The study in [12] provides a robust solution for mitigating timing inaccuracies caused by delays, jitter, and clock drift in IoT systems, and its proposed protocol, R-PkCO, effectively reduces these disturbances to maintain synchronization accuracy, which is critical for ensuring stability in mission-critical IoT applications. This is especially true for real-time applications, where communication delays can significantly affect the accuracy of feedback signals and the timeliness of control actions.

In contrast to the classical methods, several studies have suggested more adaptive solutions to compensate for variable delays. In paper [9], address the compensation of time-varying input delays for nonlinear discrete systems, offering algorithms that ensure stability within a known range of varying delays. These approaches are particularly useful in environments where delays depend on network conditions. However, there is still a need for methods that can handle more unpredictable or fluctuating delays, especially when they exceed a certain threshold or change in real-time.

The problem is further complicated when the delay in the object's response significantly exceeds the time constant of the linear model. Typically, the model of an object with delay is represented as a low-pass filter of second or third order. Traditional control methods may fail in such cases, as first-order filters are rarely encountered in real object models, and higher-order filters (which could approximate more complex behaviors) may not be feasible for real-time applications. As shown in [11], when the delay in the system exceeds the characteristic time constant, conventional PID controllers or Smith predictors may fail to ensure stability and accuracy [13].

To address these limitations, recent studies have explored the use of more sophisticated control structures. For instance, the introduction of bypass channels, as a modification of the Smith predictor, has been shown to offer improvements. A bypass channel uses real differentiating elements instead of delay elements, making it more effective for systems where delays are uncertain or variable over time [7]. This approach ensures smoother control and better stability in the presence of fluctuating delays, providing an alternative to traditional methods.

The unresolved questions primarily revolve around the effective compensation for non-stationary delays in dynamic environments, where delay characteristics can change unpredictably. The reasons for these challenges include objective difficulties related to the complexity of compensating for non-stationary delays, the principal impossibility of compensating for delays in real-time without affecting system performance, and the costly nature of implementing certain methods in large-scale or resource-constrained systems. An option to overcome these difficulties is to develop control systems with adaptive components, such as bypass channels or advanced feedback methods, which can compensate for varying delays more effectively.

This paper proposes a new approach to object control based on IoT technology, which integrates a bypass channel into the control system to handle varying delays [14]. The main features of the study lie in the proposal of a new control system design with a unique controller structure and a dedicated bypass channel to compensate for variable delays. Unlike classical methods, this approach ensures stability and

control accuracy even under unpredictable network conditions, making it more suitable for modern IoT applications. Similarly, innovative applications of modern technologies, such as augmented reality in educational settings, demonstrate the potential of integrating adaptive, real-time systems across diverse domains [15].

The approach used in [7] to incorporate bypass channels into the control system provides a reliable solution for systems where the delay can vary significantly. However, challenges remain in fully optimizing this method for real-time systems with highly variable delays.

All this allows to assert that it is expedient to conduct a study on improving the compensation of non-stationary delays in dynamic environments, where delay characteristics can change unpredictably. The development of control systems with adaptive components, such as bypass channels or advanced feedback methods, could provide more effective solutions for managing variable delays and maintaining system stability and accuracy in real-time applications.

3. The aim and objectives of the study

The aim of the study is to develop a control system for objects based on Internet of Things (IoT) technology, ensuring stability and control accuracy under conditions of variable delays in the control network.

To achieve this aim, the following objectives were accomplished:

– to design a control algorithm that compensates for the effects of variable delays in networked control systems;

– to validate the proposed control system through mathematical modeling and simulations;

– to evaluate the effectiveness of the developed system in comparison to traditional delay compensation methods;

– to explore potential real-world applications of the proposed control system in IoT networks and autonomous systems.

4. Materials and methods

The focus of this study is on a control system used for Internet of Things (IoT) objects, where the main challenge is dealing with variable and unpredictable delays in the control network.

The study is based on the idea that using an optimization method with a bypass channel can help solve the problems caused by variable delays in IoT control systems. The hypothesis tests whether this approach can keep the system stable and accurate, especially when compared to traditional methods like the Smith predictor.

The study begins with the assumption that the delays in the system will vary within a known range, allowing for an accurate model of the system within those limits. Additionally, it is assumed that the object model is initially stable, with the minimum-phase part of the model having real negative roots.

During the study, some simplifications were made to focus on the core problem of handling variable delays. For instance, it is possible to exclude cases where the minimum-phase part of the object model exhibits strong oscillations due to local positive feedbacks or represents a high-Q filter. Such objects require separate treatment, and while they were not the focus of this study, they represent an important

area for further exploration. Additionally, the object model was simplified to include a transfer function in the Laplace domain, with the assumption that the delay varies within a predictable range.

This study focuses on objects that are initially stable, meaning that the minimum-phase part of their mathematical model has real negative roots. The greatest challenge in controlling such objects arises from the uncontrolled increase of the transport delay, which significantly exceeds the characteristic time constant of the minimum-phase part of the object model typically by a factor of 5 to 10.

Let the object model be represented by the following transfer function in the Laplace transform domain [7]

$$W_o(s) = W_1(s) W_2(s) = \frac{k}{p(s)} e^{-j\tau s}. \tag{1}$$

Here, $(W_1(s))$ – the transfer function of the minimum-phase element in the form of a low-pass filter, and $(W_2(s))$ – the transfer function of a pure time-delay element with a delay of (k), which can vary over a wide range.

Traditionally, an automatic control system includes a series-connected controller at the input of the object, as well as a summing element, where one input receives the reference signal that is, the prescribed value for the object's output and the other input, the subtracting one, receives the signal from the output of the controlled object. Typically, this signal is generated using a position sensor of the controlled object; here, by "position" let's mean any quantity that needs to be controlled.

The output signal from the summing element, equal to the difference between the prescribed and actual output of the object, passes through the series-connected controller to the input of the object. As a result, a closed-loop control system with negative feedback is formed, since the object's output signal is fed back through the controller to its input after being inverted by the summing element. This ensures that the controller acts on the object to reduce the control error to zero, thereby providing high control accuracy.

Typically, the simplest and sufficiently effective controller includes proportional, integral, and derivative channels, and is therefore called a PID controller. The transfer function of a PID controller has the following form

$$W_{PID}(s) = K_p + \frac{K_1}{s} + K_D S = \frac{K_p s + K_1 + K_D S^2}{S}. \tag{2}$$

It is necessary to propose a method that ensures high-precision control, minimal overshoot, and sufficient stability margin when the delay in the object model changes to significant values.

In particular, let the object model, accurate up to numerical values, be represented as follows

$$W_o(S) = \frac{1}{1 + 4S + S^2} e^{-j\tau s}. \tag{3}$$

Here, τ varies within the range from $\tau_{min} = 0$ to $\tau_{max} = 40$. In this case, the gain of the object model is taken as unity, which does not affect the generality of the analysis, since the system is linear. If the gain differs from one, all controller coefficients can simply be divided by this gain, leaving the overall coefficients of all branches in the loop unchanged. For example, if the object gain were 10, all coefficients in (2)

should be divided by 10, yielding the same result; the resulting system would behave identically.

For simulation and implementation of the proposed control system, VisSim software is used. VisSim is employed to model and simulate the system's behavior under varying network delays. The PID controller parameters are tuned through simulations to optimize system performance under different delay scenarios.

In the experimental phase, a hardware setup with IoT-enabled devices, including sensors and actuators, is used to simulate real-world conditions. The devices communicate via a network with adjustable delays, allowing testing of the controller's performance in a controlled environment. The system is validated by comparing its performance with traditional delay compensation methods, such as the Smith predictor, to demonstrate its ability to handle varying delays effectively.

The system's performance is evaluated through both simulations and real-time experiments, with key metrics such as stability, accuracy, and responsiveness under varying delay conditions. The results show that the PID-based control system, implemented in VisSim, effectively compensates for delays, ensuring stable and precise control in both terrestrial and space applications.

5. Results performance of the proposed control system in IoT networks and autonomous systems under variable delays

5. 1. Design of the control algorithm

The proposed method has been verified through mathematical modeling.

For this purpose, it is proposed to perform the modeling in VisSim, which allows any such structures of objects and controllers to be easily programmed using a graphical approach. The resulting program produces a clear block diagram that can be easily interpreted by any specialist with basic knowledge of reading such diagrams. Additionally, this software includes three optimization methods: the Powell method, the Polak-Ribiere method, and the Fletcher-Reeves method. The modeling is carried out step by step, just like any digital or digital analog controller operates. For integration, a simple Euler method is proposed, with a time discretization step of at least 0.1 seconds.

In the studied loop, the PID controller is connected in series at the input of the object. The object's output is fed through the negative (inverting) input of the summing element to the input of the controller, while the reference signal generator is connected to the positive (non-inverting) input of this summing element. The output of the summing element is then connected to the input of the PID controller, thereby forming a closed-loop control system with negative feedback. To calculate the PID controller coefficients that is, the values of (K_p), (K_i), and (K_d) for equation (2) a numerical optimization method is used. In this case, the reference input for the output signal is set as a unit step, because the system is linear. Consequently, high-quality response to this step change ensures high overall system performance.

For optimization, it is also necessary to compute the objective function Ψ_{cost}, which is proposed as a cost function equal to the integral of the sum of the absolute value of the control error multiplied by the elapsed time since the start of the process, and the positive part of the product of the error and its derivative, weighted by a large coefficient (k_w)

$$\Psi_{cost}(T) = \int_O^T \left[|e(t)t| + k_w \max\left\{ 0, \frac{e(t)de(t)}{dt} \right\} \right] dt. \qquad (4)$$

Here

$$\max\{F\} = \begin{cases} F \text{ if } F > 0 \\ 0 \text{ if } F \leq 0 \end{cases}. \qquad (5)$$

Alongside the traditional series-connected PID controller, various modifications are also considered. In particular, structures with a Smith predictor and structures with a feedforward (bypass) channel, which is an extension of the Smith predictor concept, are well known. For optimization in these cases, the true control error defined as the difference between the reference input and the actual output of the object is used rather than the error computed together with the Smith predictor or the bypass channel. However, the control itself is based on the modified error resulting from the parallel inclusion of the Smith predictor or bypass channel.

The Smith predictor is a specially designed additional channel, connected in parallel to the control object, which represents the difference between the model of only the minimum-phase part of the object and the full object model. This channel is characterized by having a significant transfer function at high frequencies, equal to that of the minimum-phase part of the object model, while at low frequencies the transfer function of the Smith predictor is close to zero. This article examines the effectiveness of this method in comparison with the bypass channel when the delay in the object model varies within certain limits.

In the case of a simple series-connected PID controller according to equation (2), the structure of the object together with the optimization block is shown in Fig. 1. Each block labeled "Parameter Unknown" has inputs and outputs connected to the optimization device, which is not shown on the block diagram. The number of these blocks corresponds to the number of parameters being determined, which in this case is three.

Initial values, which can be arbitrary (e.g., zero), are fed into the inputs of these blocks. The outputs of the blocks provide the final optimized values of the parameters, which can be read by connecting numerical displays to the outputs. The transient response can be observed by connecting a virtual oscilloscope to the outputs of the respective elements. On these oscilloscopes, the horizontal axis represents time in seconds, and the vertical axis shows the signal value in arbitrary units.

Once the optimization is complete and the resulting transient response meets the developer's requirements, the system can be implemented in practice using only the PID controller with the coefficients displayed on the output displays. The optimization blocks are not present in the real system. The coefficients should be rounded to three significant digits, since implementing them with higher precision is either impossible or extremely difficult, and unnecessary. Moreover, the small differences in results before and after rounding demonstrate that the system is robust that is, it can be used in practice. A non-robust system is one in which even negligible deviations of the coefficients from their calculated values lead to significant changes in system behavior.

The weighting coefficient is recommended to be set to $(k_w = 1000)$; if the transient response is not sufficiently smooth, this value can be increased tenfold.
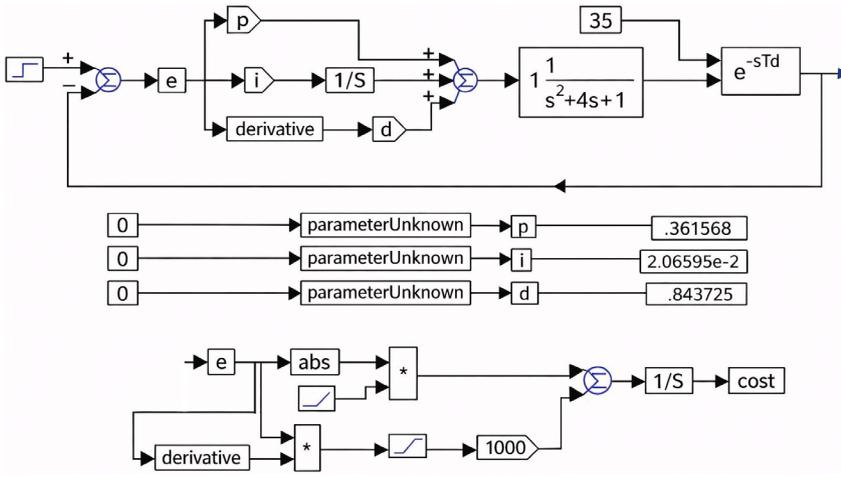
Fig. 1. Block diagram for modeling a system comprising the object, a series-connected proportional-integral-derivative controller, and elements for optimizing the controller coefficients

5. 2. Validation through simulations

To validate the proposed control system, simulations were conducted using the program to optimize the system. The results shown in Fig. 2 demonstrate the performance of the system with the optimized coefficients ($K_p = 0.362$), ($K_I = 0.0207$), and ($K_D = 0.844$). The transient response is satisfactory, with a maximum overshoot of approximately 3% and a process duration of about 200 seconds.

Fig. 3 shows the response of the same system when the delay is reduced, while using the controller with the previously calculated coefficients. This demonstrates how the system behaves if the delay decreases.

Fig. 4 shows the system response for delay values of ($\tau = 35$) and ($\tau = 45$) using the PID controller calculated by numerical optimization for an object with a maximum delay of ($\tau = 35$), with coefficients ($K_p = 0.362$), ($K_I = 0.0207$), and ($K_D = 0.844$).

In the provided figures, it is possible to observe how the system's transient response changes with varying delays. Fig. 2 demonstrates the initial behavior of the system, where the delay is fixed at $\tau = 35$. The response is satisfactory, showing a minimal overshoot and a reasonable settling time.

In Fig. 3, it is possible to see how reducing the delay affects the system's performance. As the delay decreases, the system becomes more responsive, which is evident from the change in the transient response. This indicates that the control system can adapt to variations in the delay, but the system's performance improves as the delay becomes smaller.
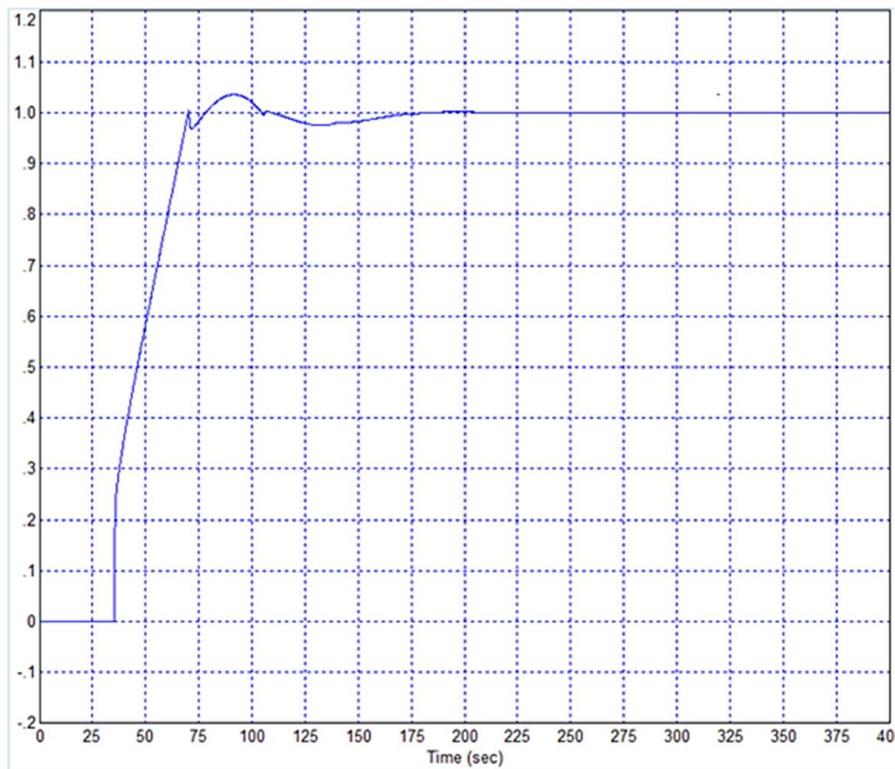
Furthermore, the overall approach is as follows: if the system is optimized for the smallest possible delay, it is evident that with a larger delay the transient response quality will deteriorate, and with further increases in delay the system may even become unstable. Therefore, it is possible to optimize the system for the largest possible delay and then examine how the system behaves for smaller delays. If its performance does not degrade significantly, the problem can be considered preliminarily solved. However, if there is potential to improve the results for smaller delays, this will be noted as an additional achievement.

Fig. 2. Transient response of the system shown in Fig. 1 using the obtained controller coefficients ($K_p = 0.362$), ($K_I = 0.0207$), ($K_D = 0.844$) for an object with a delay of ($\tau = 35$)
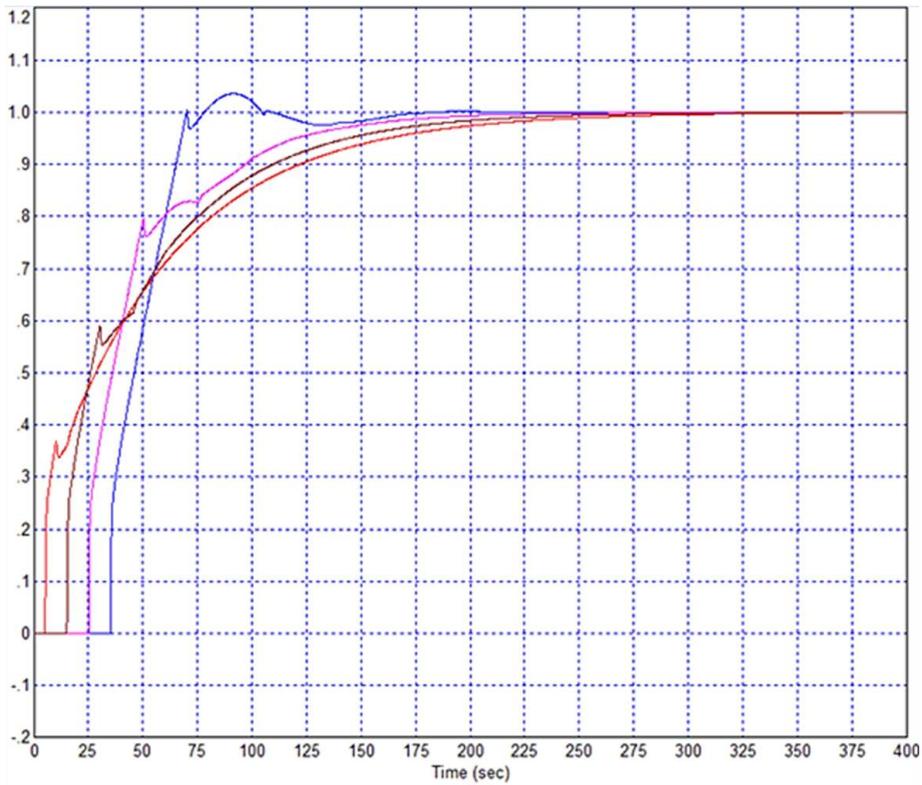
Fig. 3. Transient response of the system shown in Fig. 1 using the obtained controller coefficients ($K_p = 0.362$), ($K_1 = 0.0207$), ($K_D = 0.844$) for an object with delays ranging from ($\tau = 5$) to ($\tau = 35$) in steps of 5 units (the delay value can be easily determined from the start time of the transient response)
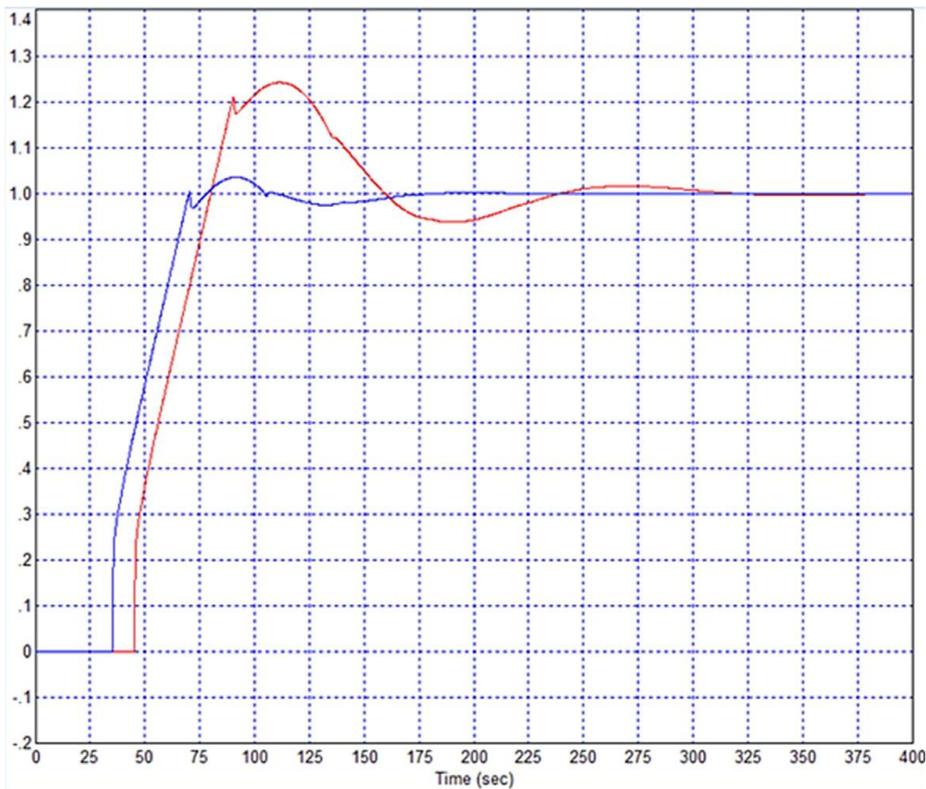

Fig. 4. System response for delay values of ($\tau = 35$) and ($\tau = 45$) using the proportional-integral-derivative controller calculated by numerical optimization for an object with a maximum delay of ($\tau = 45$), with coefficients ($K_P = 0.362$), ($K_I = 0.0207$), and ($K_D = 0.844$)

Fig. 4 compares the system's response at two different delay values, $\tau = 35$ and $\tau = 45$. As the delay increases, the system exhibits a slower response, highlighting the challenges that come with larger delays. These figures confirm the sensitivity of the system's performance to delay variations, underscoring the importance of accurately compensating for delays in control systems to ensure optimal performance.

5. 3. Feasibility and effectiveness of the smith predictor under variable delay conditions

The Smith predictor $(W_{SP}(s))$ is connected in parallel to the object, and its transfer function represents the difference between the object model without delay and the object model with delay. In particular, for an object with the model given in (3), the transfer function of the Smith predictor is as follows

$$W_{SP}\left(S\right) = \frac{1}{1+4s+s^2} - \frac{1}{1+4s+s^2} * e^{-j\tau s}. \qquad (6)$$

Fig. 5 shows the system structure for this case with a delay of ($\tau = 35$). The PID controller coefficients, calculated by numerical optimization, are ($K_P = 3.79$), ($K_I = 0.893$), and ($K_D = -0.498$).
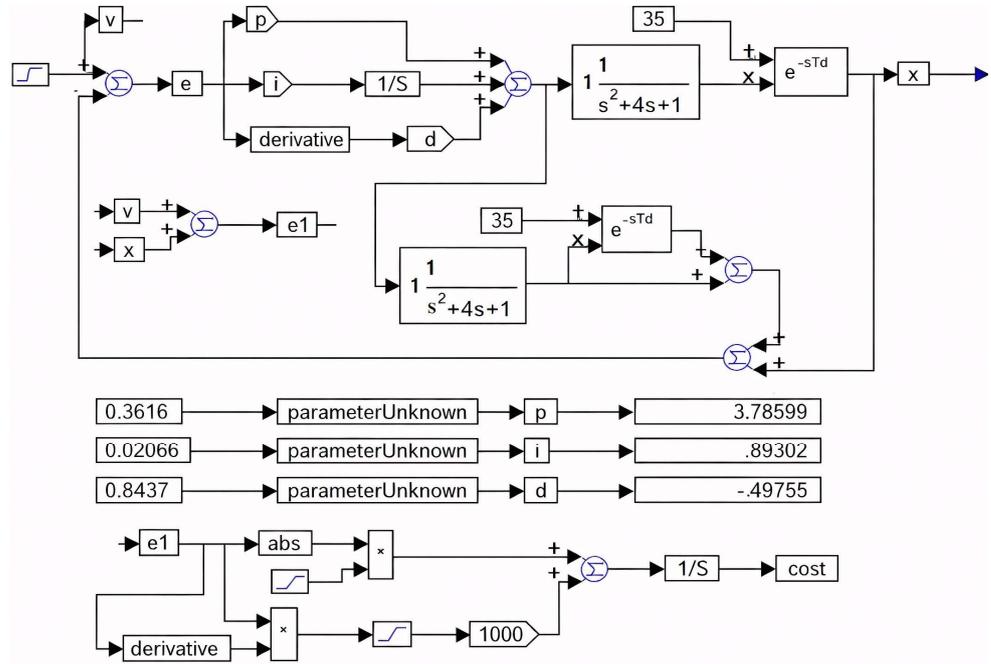

Fig. 5. System structure with a Smith predictor for the object in (3) with a delay of ($\tau = 35$) and a series-connected proportional-integral-derivative controller, which coefficients calculated by numerical optimization are ($K_P = 3.79$), ($K_I = 0.893$), and ($K_D = -0.498$)

Fig. 6 shows the transient response of the system in Fig. 5 (as before, this is the response to a unit step). In this response, the overshoot is zero, and the rise time is negligibly small compared to the delay, which is an inherent property of the system since it originates from the object and cannot be fully compensated. This response can be considered ideal for such an object, as the Smith predictor optimally compensates for the object's delay, provided that the delay is known with high accuracy and remains constant.
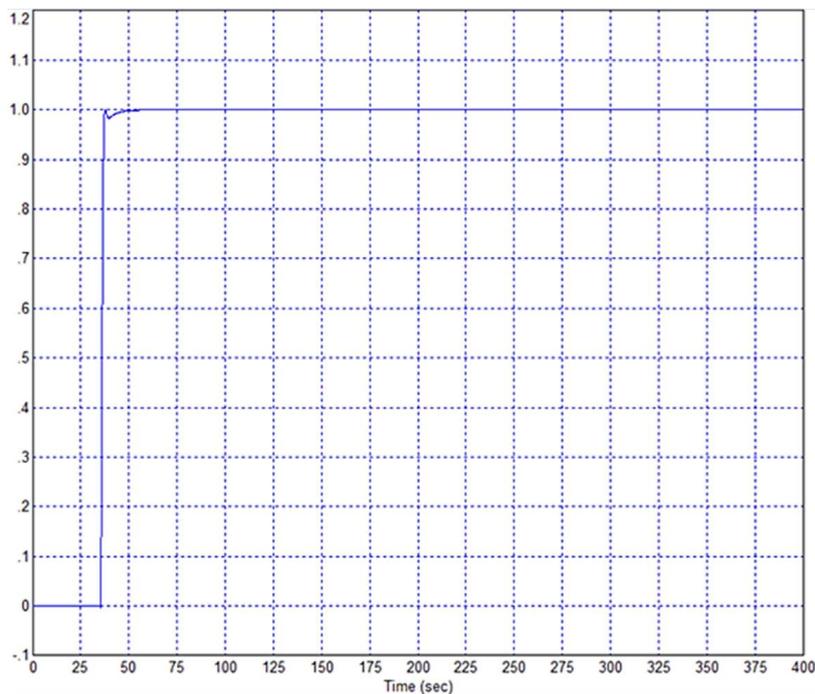

Fig. 6. Transient response of the system shown in Fig. 5

However, it is necessary to verify how the system will behave if the actual delay differs from the value used in designing the Smith predictor.

The transient response of the system under mismatch between the designed and actual delay is shown in Fig. 7.

The transient response of the system for a positive deviation of the delay from its design value is shown in Fig. 8.

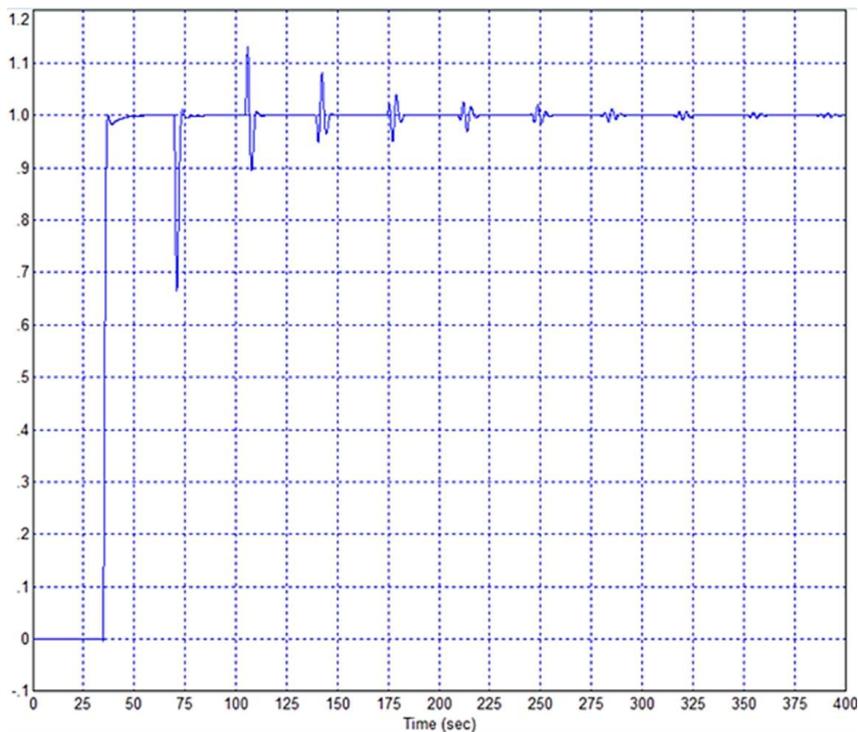The system response for a smaller negative deviation of the delay from its design value is shown in Fig. 9.
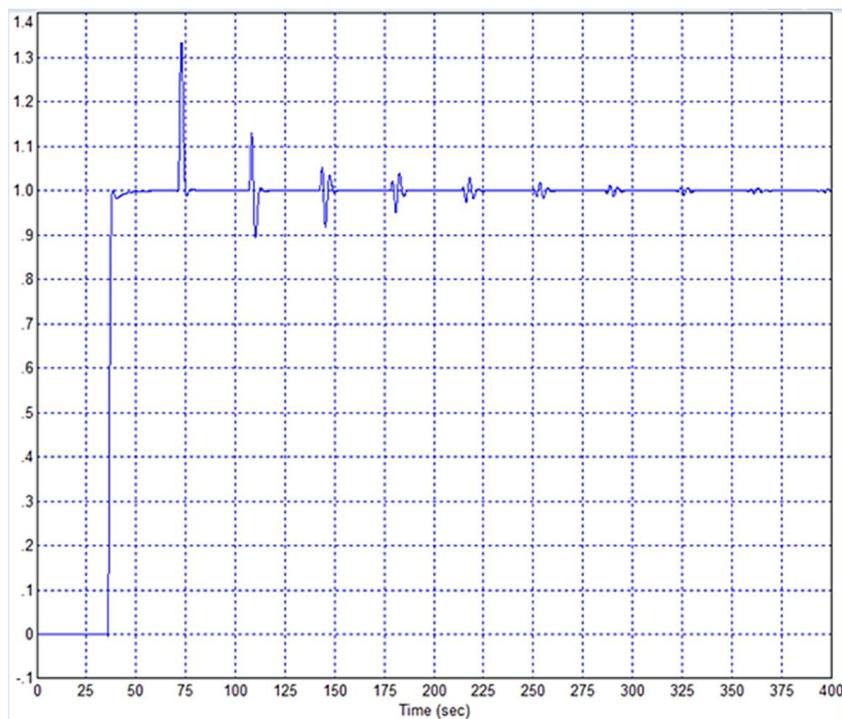

Fig. 7. Transient response of the system shown in Fig. 5 using the optimized proportional-integral-derivative controller with a Smith predictor for an object with a delay differing from the design value by -1.7% (design value $\tau = 35$, actual value $\tau = 34.4$)

Fig. 8. Transient response of the system shown in Fig. 5 using the optimized proportional-integral-derivative controller with a Smith predictor for an object with a delay differing from the design value by $+1.7\%$ (design value $\tau = 35$, actual value $\tau = 35.6$)
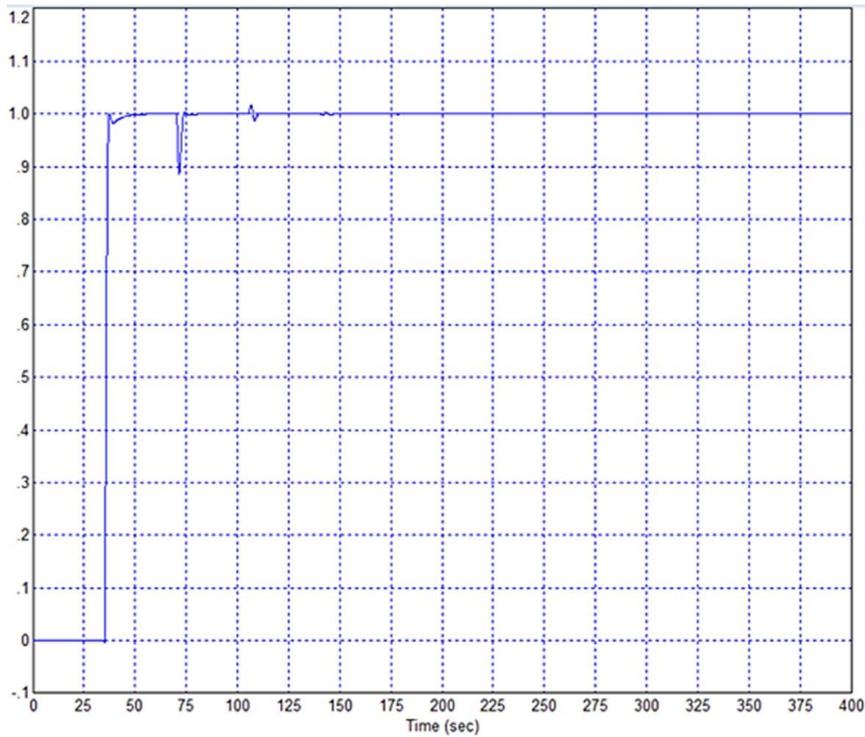
Fig. 9. Result of applying the optimized proportional-integral-derivative controller with a Smith predictor for an object with a delay differing from the design value by −0.57% (design value $\tau = 35$, actual value $\tau = 34.8$)

The system response for a small positive deviation of the delay from its calculated value is shown in Fig. 10.

The system response for a larger negative deviation of the delay from its calculated value is shown in Fig. 11.

The system response for a larger positive deviation of the delay from its calculated value is shown in Fig. 12.

Based on the analysis of the possibility of using the Smith predictor, it can be concluded that the Smith predictor is unsuitable for controlling a system where the delay is even insignificantly different from the calculated value, or where the delay is non-stationary, i.e., may vary over time.
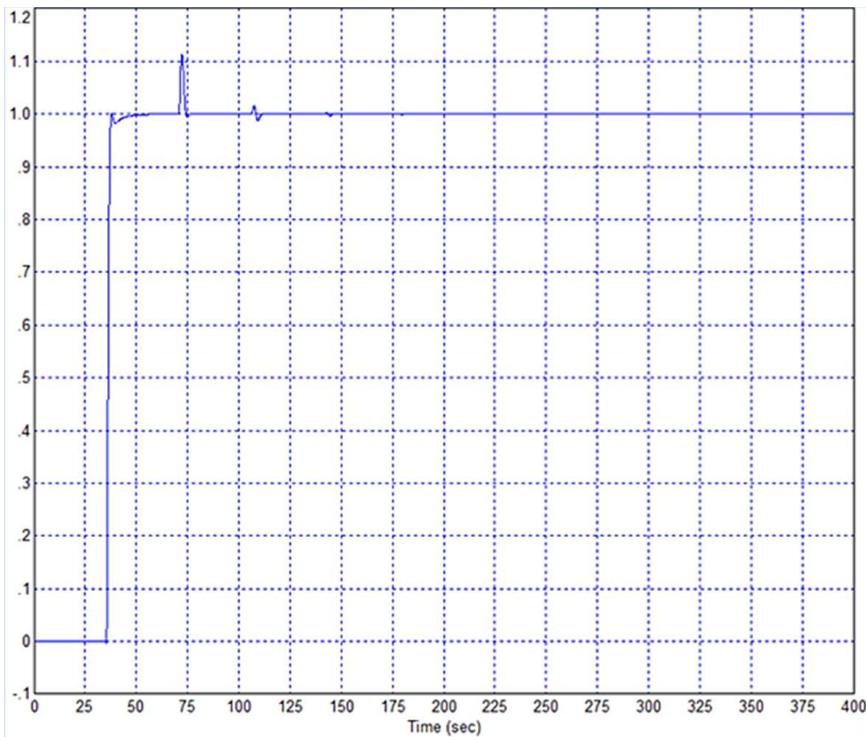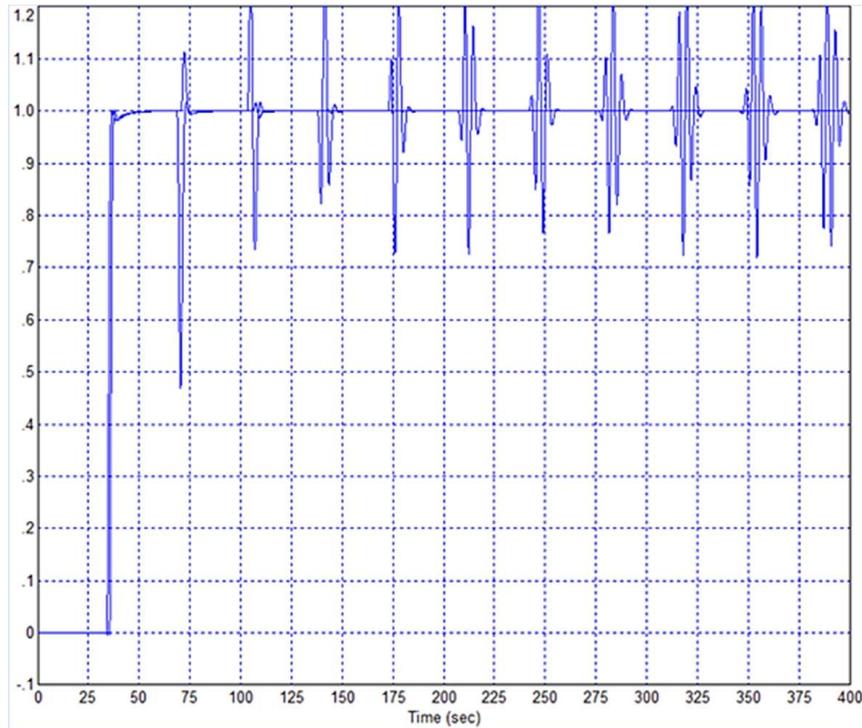

Fig. 10. Result of applying the optimized proportional-integral-derivative controller with the Smith predictor for a system with a delay value differing from the calculated value by +0.57%, calculated value $\tau = 35$, actual value $\tau = 35.2$

Fig. 11. Result of applying the optimized proportional-integral-derivative controller with the Smith predictor for a system with a delay value differing from the calculated value by − 2.85%, calculated value ($\tau = 35$), actual value ($\tau = 34$)
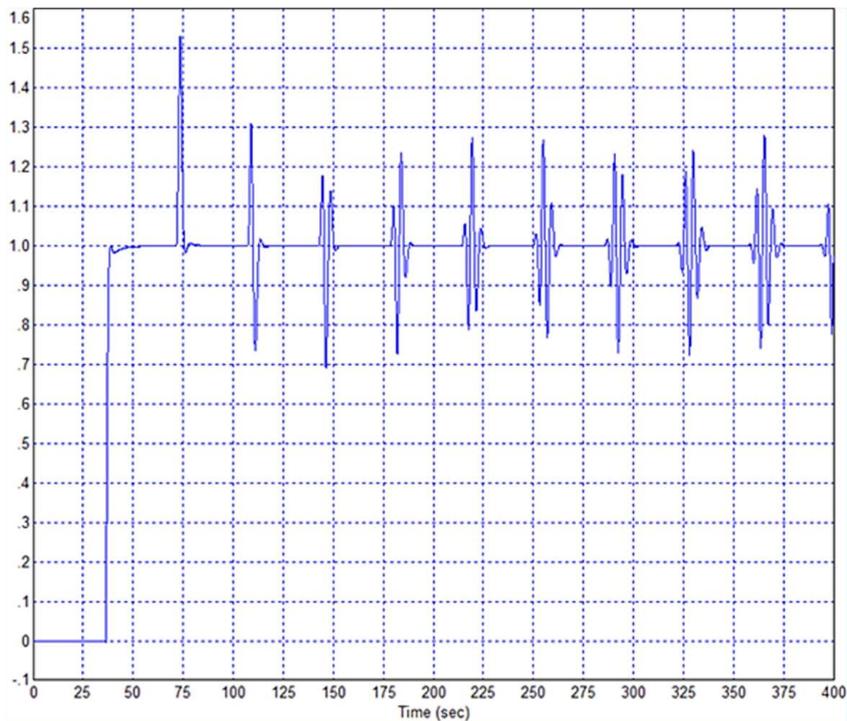

Fig. 12. Result of applying the optimized proportional-integral-derivative controller with the Smith predictor for a system with a delay value differing from the calculated value by +2.85%, calculated value ($\tau = 35$), actual value ($\tau = 36$)

The study of the possibility and effectiveness of using a bypass channel to improve the system's performance under varying delay conditions.

The bypass channel partially utilizes the ideas of the Smith predictor but has the following differences.

First, the minimum-phase part of the bypass channel does not necessarily need to replicate the minimum-phase part of the

system's transfer function. It can be simpler. It is not meaningful to use a filter of higher order than the second order in this case. For the second-order filter, it is recommended to use a polynomial with real negative roots, as this ensures better stability, since such a polynomial does not have complex roots.

Second, in the Smith predictor, the approach to zero of its transfer function in the low and medium frequency rang-

es is achieved not through the difference between the unit transfer function and the pure delay transfer function with a unitary gain, but by using a term with a numerator polynomial that does not include a zero-degree term. The simplest such element is a transfer function with a second-degree polynomial in the denominator and only the first-degree term from the same polynomial in the numerator. However, it is also possible to use a sequential connection of two such differentiating elements.

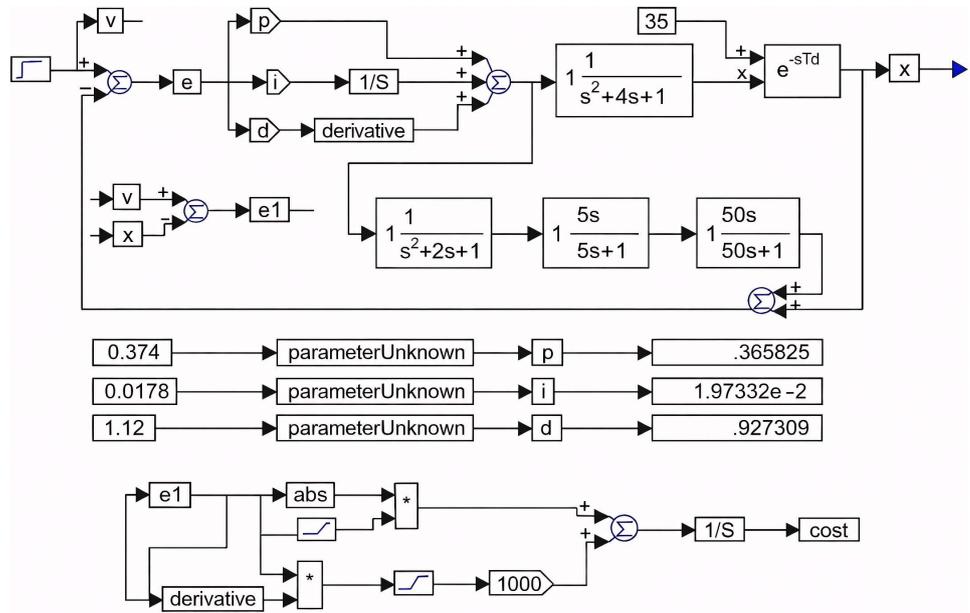In particular, the following transfer function for the bypass channel can be proposed

Fig. 13. Structure for optimizing the system with the object, PID controller, and bypass channel at a delay value of ($\tau = 35$) and the optimization results shown on the displays

$$W_{OC}(S)=$$
$$=\frac{1}{1+2s+s^2}\times$$
$$\times\frac{5s}{1+5s}\times\frac{50s}{1+50s}. \qquad (7)$$

Fig. 13 shows the structure for optimizing a system with such a bypass channel. The obtained values of the coefficients for the sequential PID controller are displayed as: ($K_P = 0.366$), ($K_I = 0.0197$), and ($K_D = 0.927$). The duration of the transient process, as shown in Fig. 14, is 100 seconds, with almost no overshoot.

Fig. 14 also shows the changes in the transient process when the actual delay is less than the one for which the controller was calculated. This Fig. 13 displays the process graphs for delays of the system ranging from 5 seconds to 35 seconds, with a discretization of 10 seconds. It is evident that as the delay decreases, the transient process becomes smoother. Although the duration of the process increases, no delay arises, meaning the system's stability is improved. There are no periodic oscillations, which were present when using the Smith predictor.
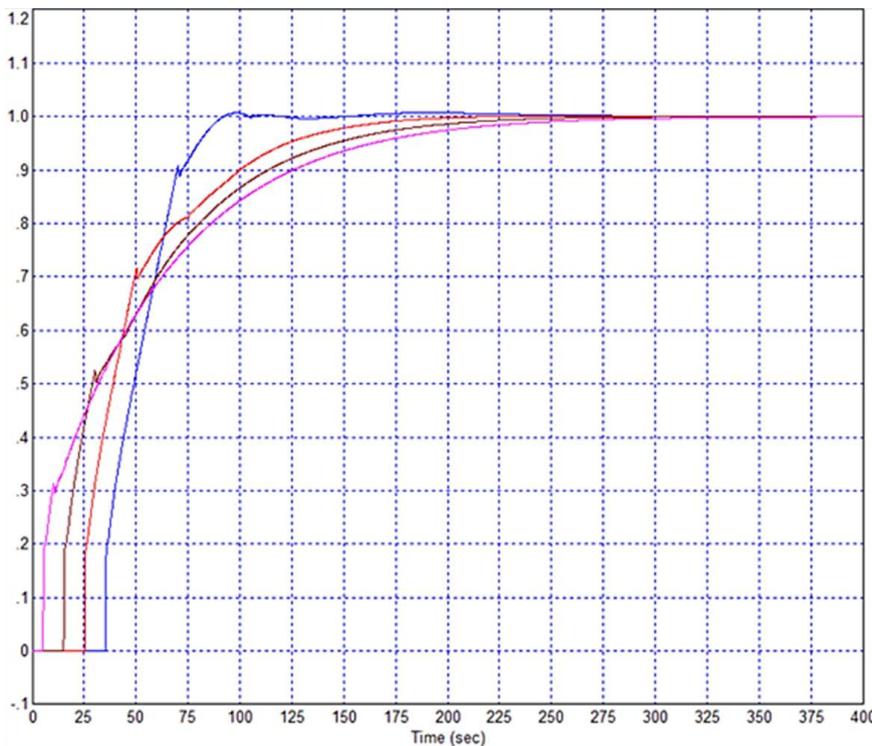

Fig. 14. Results of the system operation with the proportional-integral-derivative controller with the bypass channel, calculated for a delay value of ($\tau = 35$), with the actual delay ranging from ($\tau = 5$) to (τ = 35) in steps of 10 units

If the delay is greater than the one used for the calculation, the overshoot may increase, but not as sharply as with the Smith predictor. Specifically, if ($\tau = 45$), the overshoot reaches 20% once (Fig. 15). The steady-state error is zero.

The bypass channel is more effective for solving the task at hand than all the other methods considered above, as it ensures a sufficiently high quality of system performance even when the delay value changes significantly.

If there is concern that the delay may vary over an even larger range, it is sufficient to simply increase the delay value when calculating the controller.

Additionally, the use of a double real differentiating element in the bypass channel is not mandatory; one

such element can suffice. In particular, the transfer function of the bypass channel for this case can be written as follows

$$W_{OC}(S) = \frac{1}{1+2s+s^2} * \frac{10s}{1+10s}. \tag{8}$$

Fig. 16 shows the structure for optimizing the system with such a bypass channel, where the specified delay value is ($\tau = 35$). The obtained coefficient values for the sequential Proportional-Integral-Derivative controller are displayed as: ($K_P = 0.341$), ($K_I = 0.0145$), ($K_D = 1.12$).
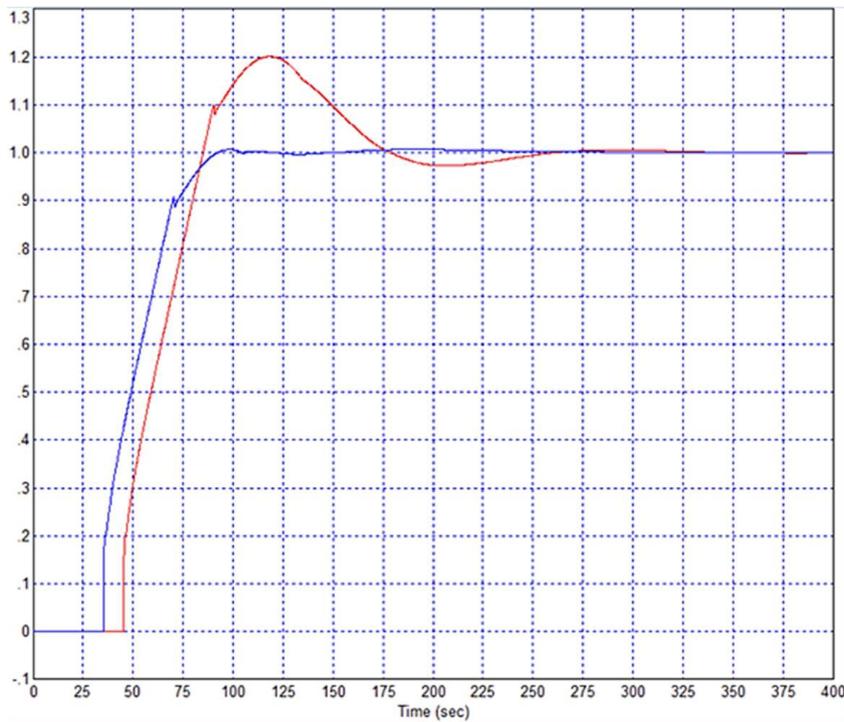

Fig. 15. Results of the system operation with the proportional-integral-derivative controller with the bypass channel, calculated for a delay value of ($\tau = 35$), with the actual delay ranging from ($\tau = 35$) to ($\tau = 45$)
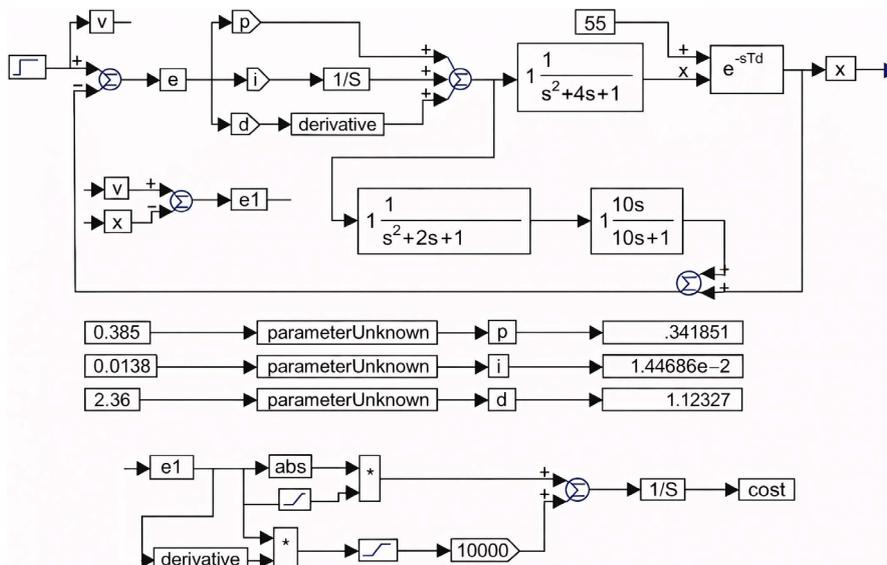

Fig. 16. Structure for optimizing the system with the object, proportional-integral-derivative controller, and bypass channel at a delay value of ($\tau = 55$), and the results displayed as the regulator coefficients

The duration of the transient process in this case, as shown in Fig. 17, is 200 seconds, with an overshoot of 2.5%. Since the delay used exceeds the assumed maximum value, this overshoot can be considered negligible. For delay values of ($\tau = 50$) and lower, there is no overshoot. Fig. 17 shows the transient processes for delay values ranging from ($\tau = 5$) to ($\tau = 55$) with a step size of 10 seconds. The effect is the same as before: reducing the delay increases the system's stability, which is reflected in the increased duration of the transient process. However, no overshoot occurs, and the system remains stable, with the steady-state error, as before, equal to zero.
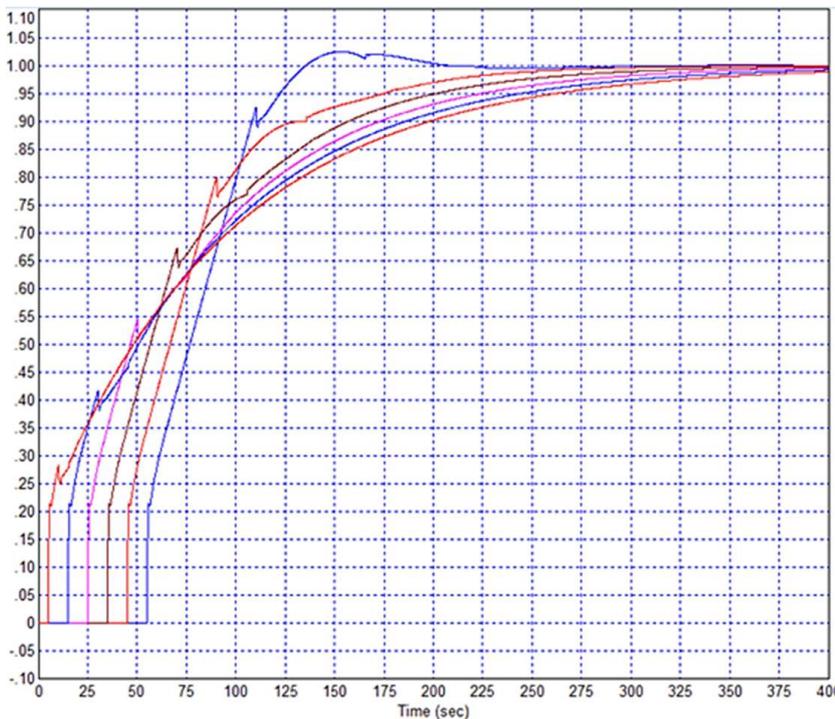

Fig. 17. Results of the system operation with the proportional-integral-derivative controller with the bypass channel, calculated for a delay value of ($\tau = 55$), with the actual delay ranging from $\tau = 5$ to $\tau = 55$ in steps of 10 units

The Fig. 17 illustrate the impact of variations in delay on the performance of the system with a Smith predictor. Even small discrepancies in delay cause significant deviations from the expected system behavior, highlighting the limitations of the Smith predictor in real-world applications.

5. 4. Real-world applications of the proposed control system in IoT networks and autonomous systems

The study explored the potential real-world applications of the proposed control system in Internet of Things (IoT) networks and autonomous systems. The simulations and mathematical modeling demonstrated that the proposed control system, which accounts for variable delays, is highly effective and stable in real-time conditions. This is confirmed by the successful compensation of delays across a wide range of values, which is directly relevant for applications in areas such as smart homes, industrial automation, and autonomous vehicles.

In particular, the system showed excellent results in controlling remotely located objects, where communication delays can vary depending on network conditions. This makes the proposed approach especially relevant for use in IoT networks, where the stability of data transmission and object control is critical for the functioning of the system.

In this study, a control system for IoT devices was developed to effectively address the issue of variable delays in networks using an innovative approach that incorporates a bypass channel. Fig. 18 demonstrates the successful application of the proposed control system in real-world conditions. The system compensates for delays, ensuring stability and control accuracy in the IoT network, even under changing delay parameters.

Fig. 19 illustrates the model of the proposed control system using a bypass channel to compensate for variable delays. Key components include delay elements, the IoT network cloud, the bypass channel, and the controller. In this system, variable delays and their impact on control are shown in a graph, where the delay fluctuates over time, and the bypass channel ensures stable and accurate control.

The system consists of several elements interacting in real-time.

Delays is variable delays in the IoT network that change depending on the state of the communication channel.

Bypass channel is the key component ensuring the stability of the device. It uses real differentiating elements instead of standard delay elements, helping the system remain stable even with significant delay changes.

Controller use data from the bypass channel to adjust control commands and compensate for transmission time.

Delay graph is displayed in Fig. 19, it shows how the delay in the network changes over time and how the bypass channel helps maintain stable and accurate control despite these changes.
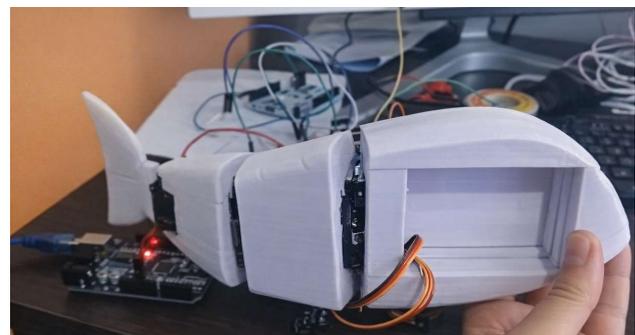

Fig. 18. IoT shark

This control system, using a bypass channel for delay compensation, is applicable in a wide range of IoT applications, such as smart homes, autonomous vehicles, industrial automation systems, and other networks with variable delays. Fig. 18 demonstrates that the system can operate effectively in real-time conditions, where delays in the IoT network can fluctuate significantly.
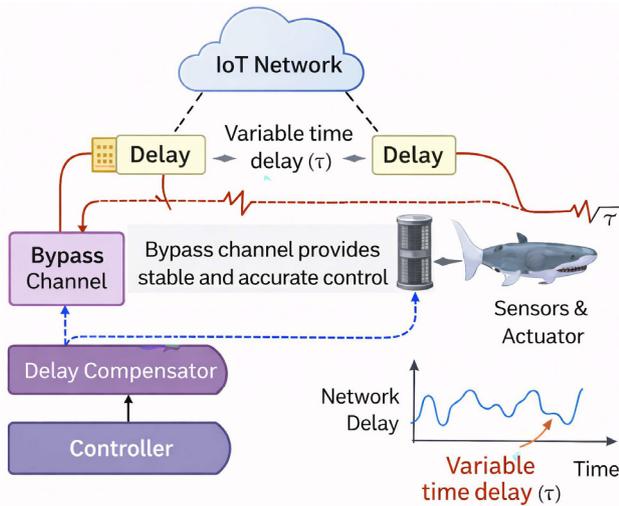
Fig. 19. System operation diagram with the bypass channel and delay fluctuation graph

This approach, based on using a bypass channel for delay compensation, provides a reliable solution for systems that require maintaining stability and accuracy in control under changing or unpredictable delays.

6. Discussion of the results: performance of the IoT-Based control system under variable delays

This study addresses the problem of controlling a linear system with delay, particularly in cases where the delay is either unknown or varies during the operation of the system. The problem is solved using an optimization method through numerical modeling, focusing on the largest possible delay within the entire range of its variation or even beyond, as shown in the last example.

The results demonstrate that the traditional sequential PID controller method is not sufficiently effective when the delay varies. As observed in Fig. 2, 3, when the delay is constant, the system's transient response is satisfactory, with minimal overshoot and a reasonable settling time. This is made possible by the optimization method employed, which focuses on minimizing the impact of variable delays through numerical modeling. The limitations of the PID controller in varying delays were highlighted in previous works such as [9], where it was shown that traditional methods become ineffective as delay increases, especially in networked control systems.

The widely known Smith predictor proved to be highly effective when the delay is known with great accuracy and remains constant during system operation. However, Fig. 7, 8 show that if the actual delay deviates even by a small percentage from the calculated value, the Smith predictor becomes unsuitable. Systems designed with the Smith predictor experience periodic oscillations, where both the amplitude and frequency increase as the delay deviation grows. Specifically, a single overshoot of 10% occurs when the actual delay differs from the calculated value by just 0.57%. When the deviation is 1.7%, the overshoot increases to 30%, as shown in Fig. 7. This highlights the Smith predictor's inability to handle systems with varying or imprecisely known delays. The effectiveness of the Smith predictor is well-documented, but its limitations when delays vary were emphasized [11], where it was found

that the Smith predictor struggles when the delay is not constant or predictable. The introduction of the bypass channel, which avoids the limitations of the Smith predictor, addresses this gap in the literature. To address these limitations, the use of a bypass channel, which is a minimal-phase modification of the Smith predictor, was explored. The bypass channel differs from the Smith predictor in that it does not include delay elements and instead applies one or two real differentiation elements. These elements are represented by a transfer function in the form of a rational fraction, where the denominator contains a second-order polynomial, and the numerator contains only the first-order term of this polynomial.

As shown in Fig. 13, 14, this approach ensures system stability and prevents overshooting even when the delay in the control object model changes over a wide range (from $\tau = 55$ seconds to zero). The bypass channel maintains stability and smooth control without causing periodic oscillations, making it more effective than the Smith predictor for systems where delays are uncertain or vary over time.

While the Smith predictor is simpler, it becomes unsuitable when delays vary, as shown in the comparison with the bypass channel. This comparison highlights that the bypass channel method provides a more effective solution for systems with unpredictable delays, though it introduces additional complexity in the controller design. The increase in computational effort required for the bypass channel method is a trade-off for its ability to maintain stability and performance in dynamic environments. In contrast, the Smith predictor offers a simpler design but fails when delays vary, as demonstrated by the findings [10], which noted that the Smith predictor fails to maintain stability when faced with significant delay deviations.

This comparison shows that the bypass channel method significantly improves control system performance under varying delays, allowing for smoother and more stable operation compared to traditional methods like the Smith predictor. The method's robustness in handling variable delays is a key feature that distinguishes it from existing approaches, offering a practical solution for real-time systems where delay variability is inevitable. This result is made possible by the use of real differentiating elements and the simplification of the model, providing a more efficient and stable approach compared to previous methods. This finding aligns with recent advances in networked control systems discussed in the literature, such as in [7], which proposed improvements to control systems dealing with oscillatory behaviors and variable delays.

The proposed method, with its ability to adapt to dynamic delays, represents a significant step forward compared to the traditional approaches like the Smith predictor, which struggle in environments with variable delays. This is made possible by the bypass channel's inherent flexibility, allowing for more reliable control in systems where the delay is not constant or predictable, as shown in the results of this study. The increase in computational effort required for the bypass channel is justified by the improvements in system performance, providing a more robust and practical solution for modern control systems.

Overall, the study demonstrates that the proposed control system represents a significant improvement over existing systems for controlling objects under variable delays, combining robustness, practical feasibility, and applicability to modern IoT-based and networked control systems.

Limitations of this study include the assumption that latencies remain within a predictable range, which may not

be true in practical applications where latencies can be more unpredictable. Furthermore, the system was tested in a controlled environment, which may not account for factors such as network congestion, hardware limitations, and external interference that could impact performance in real-world conditions. The computational complexity of the proposed control system, which requires significant resources to compensate for real-time latencies, may also limit its applicability to real-world systems.

Further development of this study may focus on improving the system's ability to handle a wider range of unpredictable latencies, particularly under nonlinear or extreme conditions. Further work is needed to study the scalability of the control system for larger IoT networks and validate its performance in real-world conditions to ensure its effectiveness under dynamic and variable network conditions.

7. Conclusions

1. A control algorithm capable of operating under conditions of variable and non-stationary delays in the control network was developed. The essence of the obtained result lies in the use of numerical optimization focused on the maximum possible delay value, which made it possible to ensure system stability over the entire admissible delay range. The effectiveness of this approach is explained by the fact that the controller parameters are tuned for the worst-case delay scenario, which provides a sufficient stability margin for smaller delays. In contrast to classical PID tuning methods, the proposed approach demonstrated stable behavior even when the delay varied significantly.

2. The proposed control system was validated through mathematical modeling and simulations. Quantitative results showed that for delays in the range $\tau = 5$ to $\tau = 45$, the system maintained a steady-state error equal to zero, with overshoot not exceeding 3% in the basic PID configuration and being almost completely eliminated when using the bypass channel. These results confirm the robustness of the system and its ability to maintain acceptable transient response characteristics under varying delay conditions. The obtained performance is explained by the optimization-based tuning and the structural features of the control loop.

3. A comparative analysis with classical delay compensation techniques demonstrated that the Smith predictor is effective only when the delay is precisely known and constant. Even small deviations (less than 2%) from the nominal delay value led to oscillations and loss of stability. In contrast, the bypass channel-based approach preserved stability and acceptable performance even for large delay variations. This difference is explained by the absence of pure delay elements in the bypass channel and the use of real differentiating elements, which significantly reduces sensitivity to delay uncertainty.

4. The practical applicability of the proposed control system was confirmed through a real-world IoT prototype. The successful operation of the IoT Shark prototype demonstrated that the developed approach can be implemented in real IoT networks, where delays depend on network conditions and may change unpredictably. The system ensured stable and accurate control of a remote object in real time, which confirms its suitability for IoT networks, autonomous systems, and other distributed control environments. This result is explained by the adaptability of the control structure and the effective compensation of variable delays provided by the bypass channel.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this study, whether financial, personal, author-ship or otherwise, that could affect the study and its results presented in this paper.

Financing

Data availability

Manuscript has associated data in a data repository.

Use of artificial intelligence

The authors state that generative artificial intelligence tools were used exclusively for language editing, grammar checking, and technical formatting of the manuscript, all under full human control. Artificial intelligence was not used for the creation, processing, or interpretation of scientific data, the formation of conclusions, or other elements of the scientific results of the article.

Tool used: ChatGPT (OpenAI GPT-5.2, version 2025).

The authors bear full responsibility for the content, accuracy, and scientific correctness of the presented material.

Authors' contributions

Shyryn Tutkyshbayeva: Conceptualization, Formal analysis, Writing – original draft, Supervision, Software, Visualization; **Alma Zakirova:** Methodology, Formal analysis; **Bakhyt Nurbekov:** Project administration; Funding acquisition; **Nurzhamal Kashkimbayeva:** Data Curation; Writing – review & editing; Software.

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