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Application of the ITAE Criterion for the Auto-Tuning of PID Controllers

Abstract:
Proper tuning of automatic controllers to meet technological process requirements is one of the key procedures during commissioning. Its outcome directly impacts product quality and process performance. The subject of the study is the process of automatic tuning of PID controller parameters based on relay feedback identification and optimization with respect to the ITAE criterion. The object of the study is a closed-loop automatic control system with an inertial self-regulating plant, typical of thermal power engineering applications, including temperature and furnace draft control loops. The study aims to develop and validate an express auto-tuning method for PID controllers that ensures minimization of the ITAE performance criterion by establishing analytical dependencies between optimal controller parameters and critical points obtained from a relay identification experiment. The article proposes a methodology for the automatic tuning of PID controller parameters to ensure the minimum of the ITAE. The rationale for the feasibility of PID controller auto-tuning is presented, along with a comprehensive analysis of existing auto-tuning methods. The developed method focuses on the ITAE quality criterion for an inertial object with self-regulation. The methodology is based on estimating key points of transient processes during a relay identification experiment and subsequently applying the proposed analytical dependencies to find the optimal set of PID controller tuning parameters. The scope of the method's application corresponds to the majority of typical objects in thermal power engineering. The algorithm for finding optimal settings holds potential for implementation in modern industrial controllers as an automatic sequence of actions. This sequence includes object identification, calculation of controller tuning parameters, and the installation of the obtained values into the PID controller. The paper presents the obtained dependencies of PID controller parameters on the properties of the control object and the results of simulating a closed-loop automatic control system. Comparative studies with an existing tuning method demonstrated more than a 15% improvement in performance results and a favorable impact on the dynamics of the actuator operation. Consequently, the proposed method of auto-tuning PID controller parameters is recommended for application to objects where the response to disturbances must possess aperiodic properties.

Keywords: PID controller, auto-tuning, ITAE criterion, relay feedback, system identification.

Abbreviations:

ISA is international society of automation

$ITAE$ is integral of time-weighted absolute error,

MPC is model predictive control

PID is proportional–integral–derivative.

Introduction

Proper tuning of automatic controllers to meet technological process requirements is one of the key procedures during commissioning. Its outcome directly impacts product quality and process performance. Although MPC is currently considered the state-of-the-art approach (*Stepanets & Mariiash, 2020*), the vast majority of automatic controllers (approximately 90%) implement the PID control law (*Stepanets & Mariiash, 2018*). Recent reviews of industrial control systems indicate that despite the development of advanced algorithms, a significant percentage of PID controllers remain poorly tuned or operate in manual mode (*Borase et al., 2021*). For instance, in many PID controllers, the derivative term is disabled simply because it is difficult to tune correctly. This issue is attributed to a lack of in-depth knowledge regarding control process dynamics and automatic control theory among commissioning personnel. The consequence is incorrect tuning parameters, leading to reduced process control efficiency and lower overall plant efficiency. Therefore, significant research effort is currently focused on finding ways to minimize the human factor in the tuning process, specifically through the development of algorithms for the automatic search of optimal controller parameters.

The subject of the study is the process of automatic tuning of PID controller parameters based on relay feedback identification and optimization with respect to the ITAE criterion. The study focuses on methodological and algorithmic aspects of minimizing control quality degradation caused by improper manual tuning and the human factor in industrial control systems.

The object of the study is a closed-loop automatic control system with an inertial self-regulating plant, typical of thermal power engineering applications, including temperature and furnace draft control loops. Particular attention is given to control objects that can be adequately represented by a first-order inertial model with transport delay and are subject to disturbances and measurement noise.

The study aims to develop and validate an express auto-tuning method for PID controllers that ensures minimization of the ITAE performance criterion by establishing analytical dependencies between optimal controller parameters and critical points obtained from a relay identification experiment.

To achieve the stated purpose, the following study objectives were formulated:

- analyze existing PID controller auto-tuning approaches and identify their methodological limitations in industrial applications;
- elect a representative class of control objects and define the admissible ranges of their dynamic parameters;
- apply relay feedback identification in order to determine critical frequency characteristics of the control object;
- determine optimal PID controller parameters by minimizing the ITAE criterion using numerical optimization;
- derive analytical approximations relating the optimal PID parameters to the identified critical points;

- verify the effectiveness of the proposed auto-tuning method through simulation of a typical thermal power engineering control loop;
- compare the proposed method with an established ITAE-based tuning approach in terms of control quality and actuator dynamics.

Thus, the development of a PID controller auto-tuning method is a relevant task, and the following steps need to be undertaken:

1. Select a typical control object model structure and the ranges of its parameter variations that characterize the method's application scope;
2. Derive analytical dependencies of optimal PID controller tuning parameters on the key points of the transient process for the selected identification method;
3. Verify the performance of the proposed method on a typical control object.

Methods

The research employs a set of general scientific methods traditionally used in control engineering and applied systems analysis. Analytical methods were used to examine existing PID auto-tuning approaches and to formulate the problem of controller parameter optimization under the ITAE criterion. Mathematical modeling was applied to represent the control object as a first-order inertial system with transport delay, allowing systematic investigation of parameter sensitivity and robustness.

Numerical simulation was used as the primary tool for validating the proposed method. Simulation experiments were conducted in the Matlab Simulink environment using a stiff numerical solver with controlled accuracy to ensure reliable reproduction of transient processes. Comparative analysis was employed to evaluate the proposed auto-tuning method against a well-established ITAE-based tuning rule, enabling an objective assessment of performance improvements.

Among the specialized methods, relay feedback identification according to the Åström–Hägglund approach was used to determine the critical gain and oscillation period of the control object without requiring an explicit parametric model. This method allowed extraction of frequency-domain characteristics from time-domain experiments under closed-loop conditions.

Optimization methods were applied to determine PID controller parameters that minimize the ITAE criterion. In particular, a modified Newton method was employed to solve the nonlinear optimization problem for a wide range of plant parameters. Regression and approximation techniques were subsequently used to derive analytical expressions relating optimal PID parameters to the critical points obtained during relay identification.

Finally, performance evaluation methods specific to automatic control systems were applied, including analysis of transient response quality, actuator smoothness, and sensitivity to disturbances and measurement noise, ensuring that the proposed method satisfies both theoretical and practical industrial requirements.

Literature Review

The vast majority of auto-tuning methods involve three fundamental stages: process identification, calculation of controller parameters, and implementation of these parameters into the controller (*Gharab & Feliu Batlle, 2023*; *Li, 2023*). Works (*Muresan et al., 2022*) present auto-tuning methods based on an analytical model derived from the control object's step response. The use of analytical models requires several assumptions; for instance, the object is often described by a first- or second-order model. Furthermore, object nonlinearities are frequently neglected specifically the omnipresent "saturation" nonlinearity system delay is assumed to be purely transport delay, and differentiation errors are ignored. Due to these assumptions, identification errors arise, rendering the controller tuning suboptimal.

Another identification approach involves obtaining the object's frequency response using a relay experiment. This identification method is the most widely used for PID auto-tuning (*Muresan et al., 2022*; *Stepanets & Mariiash, 2018*) and relies on inducing limit cycles (self-oscillations) within the system. The advantages of this method include the ability to obtain frequency characteristics for objects of any order and its implementation simplicity (*Liermann, 2013*). Some sources claim that inducing self-oscillations is dangerous for technological processes and should be avoided. However, if the amplitude of self-oscillations is limited during experiments, this mode becomes as safe as any other test signal (*Liu & Gao, 2012*).

There is also a wide range of commercial software tools available for controller tuning (*Li et al., 2006*). A typical PID tuning system consists of a computer running specialized (usually expensive) software under the Windows operating system, a set of I/O modules, and connecting cables. The object is integrated into the control loop, the system is tuned using the desired method, and the resulting controller coefficients are subsequently written to the PID controller. Thanks to a user-friendly interface, significant computing power, and the absence of restrictions on system identification algorithms, it is possible to obtain controller parameters that are close to optimal.

In addition to the studies explicitly addressed above, several authoritative works listed in the References section provide an essential theoretical and practical background for the present research. Åström and Hägglund (*2006*) offer a comprehensive treatment of advanced PID control strategies and relay-based auto-tuning methods, forming the conceptual foundation of modern industrial PID tuning. Their work systematically justifies the use of relay experiments for extracting frequency-domain information from time-domain measurements.

Blevins and Nixon (*2011*) focus on practical aspects of control loop implementation in industrial environments, emphasizing standard PID structures recommended by the ISA. Their analysis supports the choice of a classical PID controller configuration in this study and highlights the importance of consistent tuning rules for batch and continuous processes.

Seborg et al. (*2016*) provide a rigorous exposition of process dynamics and control theory, including the theoretical justification for integral performance criteria such as ITAE. Their work explains why ITAE-based optimization leads to smoother transient responses and improved robustness, which directly underpins the selection of ITAE as the objective function in the proposed method.

Furthermore, Stepanets and Mariiash (*2020*) demonstrate the advantages of advanced control strategies such as Model Predictive Control in energy systems, while simultaneously highlighting the practical constraints that limit their widespread industrial adoption. This contrast reinforces the relevance of improving PID auto-tuning algorithms that can be embedded in existing control infrastructure with minimal computational overhead.

Borase et al. (*2021*) provide a structured review of the evolution of PID control, systematizing both classical and modern tuning approaches, including Ziegler–Nichols-type rules, frequency-response-based methods, optimization-based techniques, and computational intelligence approaches. The authors demonstrate that the practical effectiveness of PID controllers in industrial applications continues to depend largely on the quality of process identification and parameter tuning procedures. For the present study, this review is particularly important because it clearly identifies typical practical limitations of auto-tuning methods—such as measurement noise, nonlinearities, actuator saturation, model uncertainty, and plant variability—thereby justifying the selection of robust performance criteria like ITAE and the development of low-computational-cost algorithms suitable for real industrial control loops.

O'Dwyer (*2009*) presents one of the most widely cited handbooks on PI and PID controller tuning rules, compiling and systematically comparing a broad range of express tuning methods for different classes of plants and performance criteria, including tuning rules aimed at minimizing integral performance indices such as ITAE. The handbook also provides practical guidance on selecting controller structures and tuning parameters based on plant dynamics, including inertia, time delay, and dominant time constants. In the context of this article, this source serves as a methodological benchmark, enabling a rigorous comparison between the proposed ITAE-oriented auto-tuning approach and established tuning rules, as well as a clear interpretation of differences in transient response characteristics and actuator loading.

Results

For this study, the standard PID controller structure was selected in accordance with ISA recommendations (*Blevins & Nixon, 2011*). The simulation procedure was performed in the Matlab Simulink environment. The ode23s (stiff/Mod. Rosenbrock) solver with a variable step size was selected. Both absolute and relative calculation tolerances were set to 0.001.

The practical implementation of auto-tuning is based on the Åström-Hägglund Relay method (*Åström, K. J., & Hägglund, 2006*). This PID parameter auto-tuning method is based on the analysis and processing of the object's frequency response. Its essence lies in the fact that a dynamic system with dominant aperiodic properties transmits harmonic oscillations with a frequency $\omega < \omega_c$ (where ω_c is the cutoff frequency) without changing their frequency. However, the amplitude and phase shift of the output signal depend on the frequency of the input signal (*Figure 1*). Thus, unlike step and impulse responses, which characterize the behavior of a dynamic link in the frequency range close to zero, frequency responses describe the properties of a dynamic link across the frequency range under investigation.

In the implemented auto-tuning method, a point on the Nyquist plot (frequency response locus) of the dynamic object is determined at the phase crossover frequency ω_p. To achieve this, starting from a steady state, an input test signal of a set amplitude (A) is applied in either direction. Once the output signal deviates noticeably from the initial steady-state value, the input signal is switched by a magnitude of 2A in the opposite direction (*Figure 2*). Subsequent switches of the input signal are executed at the moments when the output signal crosses the baseline of its initial value.

As a result of the experiment, the critical points K_{cr} and T_{cr} are determined. If the magnitude of the rectangular pulses at the object input equals 2A, then the amplitude of the fundamental harmonic at the object output equals $4A/_{\pi}$ To determine the value of K_{cr}, Formula (1) is used:

$$K_{cr} = \frac{4A}{\pi B} \tag{1}$$

where

A is the amplitude of the relay pulses;

B is the amplitude of the harmonic oscillations at the output;

T_{cr} is numerically equal to the period of the harmonic oscillations in seconds.

The next stage of the auto-tuning process involves calculating the PID controller tuning parameters. To calculate these parameters, express methods (*O'Dwyer, 2009*) utilizing typical simple integral criteria are most frequently employed. The Integral of the ITAE was selected as the objective function (2) for the proposed tuning method:

$$ITAE = \int t|e(t)|dt \tag{2}$$

When using ITAE, the control process quality is defined by the time-weighted error. This index minimizes the impact of the initial phase of the control process, where the deviation from the setpoint is relatively large, and places greater emphasis on errors persisting over time. Consequently, ITAE is considered a representative criterion and is widely employed in controller tuning methods, as it yields more stable and reliable transient responses (*Seborg et al., 2016*).

In the process of developing an express method ensuring the minimum ITAE (2), a simulation of the automatic control system with a PID controller was performed. The mathematical model of the research object is described by a first-order inertial link with transport delay (3):

$$W_p(s) = \frac{K_o}{T_o s + 1} e^{-\tau_o s} \tag{3}$$

The PID controller tuning parameters were determined using the modified Newton method. The objective function was ITAE. The experimental dataset was obtained by varying the dynamic properties of the control object($K_o \in [0.05 \dots 10]$, $T_o \in [2 \dots 500]$, $\tau_o \in [0 \dots 100]$). For each case, the critical points $(K_{cr},\ T_{cr})$ and the optimal PID controller tuning parameters were determined. As a result of the simulation, the dependencies of the controller tuning parameters ensuring the minimum ITAE on the critical points K_{cr} and T_{cr} were obtained (*Figure 3*; *Figure 5*).

The obtained experimental datasets (*Figure 3*; *Figure 5*) are approximated by the dependencies (4) of the PID controller tuning parameters on the critical points:

$$\begin{cases} K_p = 0{,}46 \cdot K_{cr} \\ T_i = 0{,}0045 \cdot (T_{cr})^2 + 0{,}3 \cdot T_{cr} \\ T_d = 0{,}57 \cdot T_{cr} \end{cases} \tag{4}$$

The mean squared approximation error does not exceed 3%, which is acceptable for practical application. The performance verification of the tuning method will be conducted on a typical object in thermal power engineering—a boiler unit, specifically the furnace draft control loop. Maintaining a slight draft in the upper part of the boiler furnace is necessary to ensure flame stability in the combustion zone and the removal of flue gases from the boiler. The challenges in furnace draft control include the presence of high-frequency measurement noise, external disturbances (changes in airflow rate), and internal disturbances (disruptions in the air-gas regime). The control object via the "induced draft fan speed—furnace draft" channel is described by the transfer function:

$$W_p(s) = \frac{0{,}55}{5s+1} e^{-2s} \tag{5}$$

The output of the control object, i.e., the draft sensor readings, is corrupted by high-frequency noise with a variance of 0.4664. This approximates the simulation to the real operating conditions of the automatic control system.

Let us perform the auto-tuning of the boiler furnace draft control system. The critical points (6) obtained during the active experiment (*Figure 6*) are:

$$\begin{cases} K_{cr} = 4{,}8; \\ T_{cr} = 14{,}9\ [s]. \end{cases} \tag{6}$$

The PID controller parameters obtained during the auto-tuning process are (7):

$$\begin{cases} K_p = 0{,}46 \cdot K_{cr} = 2{,}2 \left[{}^{\%}/_{Pa}\right] \\ T_i = 0{,}0045 \cdot (T_{cr})^2 + 0{,}3 \cdot T_{cr} = 5{,}47\ [s] \\ T_d = 0{,}57 \cdot T_{cr} = 2{,}96\ [s] \end{cases} \tag{7}$$

To compare the performance of the proposed auto-tuning method, let us calculate the PID controller tuning parameters (8) using the Modified minimum ITAE—Smith method (*O'Dwyer, 2009*) and simulate the closed-loop automatic control system.

$$\begin{cases} K_p = \frac{0{,}965}{K_o} \cdot \left(\frac{T_o}{\tau_o}\right)^{0{,}855} = 3{,}84 \left[{}^{\%}/_{Pa}\right] \\ T_i = 1{,}26 \cdot T_o = 6{,}3\ [s] \\ T_d = 0{,}308 \cdot \tau_o = 0{,}616\ [s] \end{cases} \tag{7}$$

The ITAE of the boiler furnace draft control transient process with PID parameters obtained via auto-tuning is $100\% \left(1 - \frac{4975}{6005}\right) \approx 17{,}13\%$ lower than that obtained using the Modified minimum ITAE—Smith express method (*Figure 7*).

At the same time, the controller parameters obtained via the proposed method ensured smoother actuator operation. It is important to emphasize that despite the availability of auto-tuning, the controller may fail to deliver the required control performance due to factors unrelated to the quality of the embedded algorithms. For instance, the control object may be poorly designed (coupled control loops, significant delay, high-order object); the object may be nonlinear; sensors may be incorrectly positioned or have poor contact with the object; the noise level in the measurement channel may be unacceptably high; sensor resolution may be insufficient; the actuator may exhibit excessive inertia or hysteresis; or there may be system installation errors, poor grounding, wire breaks, etc. Therefore, before initiating the auto-tuning process, it is essential to verify the absence of the aforementioned issues.

Discussion

The results of this study address the persistent challenge of the "human factor" in industrial control loops, where approximately 30% of PID controllers remain poorly tuned. While Model Predictive Control represents the theoretical state-of-the-art, the practical reality of thermal power engineering demands robust, low-resource algorithms for existing PID infrastructure.

The proposed auto-tuning method, based on relay feedback identification and ITAE minimization, demonstrated a statistically significant improvement lowering the integrated error by over 15% compared to the Modified Minimum ITAE Smith method. Crucially, this performance boost did not come at the cost of actuator wear; on the contrary, the control signal exhibited smoother dynamics, which is vital for extending the lifespan of electromechanical drives in boiler units.

However, these findings raise important questions regarding the boundaries of the method's applicability. The current algorithm is optimized for inertial objects with self-regulation, typical for temperature and draft control. A critical subject for further discussion is the method's adaptability to integrating processes (e.g., drum level control) or unstable systems, which require different stability margins. Furthermore, while the simulation accounted for high-frequency noise, the reliance on a "clean" physical setup (correct sensor placement, absence of significant hysteresis) remains a prerequisite. Future research should focus on developing adaptive mechanisms that allow the controller not only to tune itself initially but to re-tune in real-time as plant parameters drift due to equipment aging or fouling. Additionally, investigating the trade-off between the aggressiveness of ITAE minimization and the system's robustness against unmodeled structural resonances would be valuable for broader industrial adoption.

Conclusion

A method for PID controller auto-tuning based on the Integral of ITAE performance criterion has been developed for an inertial object with self-regulation. The method involves estimating key points of transient processes during a relay identification experiment and subsequently applying the proposed analytical dependencies to determine the optimal set of PID controller tuning parameters. The scope of the method covers the majority of typical objects in thermal power engineering. The algorithm for finding optimal settings holds potential for implementation in modern industrial controllers as an automatic sequence of actions, including process identification, calculation of tuning parameters, and application of the obtained values to the PID controller. Comparative studies with an existing method demonstrated an improvement in results of more than 15% and a favorable impact on actuator dynamics. The proposed PID controller auto-tuning method is recommended for objects where the response to disturbances requires aperiodic properties.

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Appendix

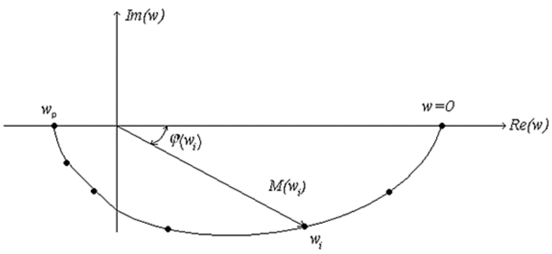

Figure 1. Nyquist plot of a system with dominant aperiodic properties

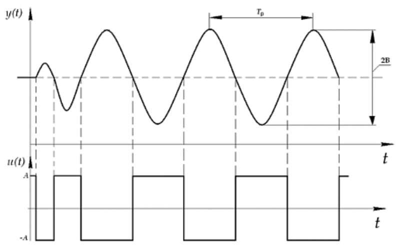

Figure 2. Experimental plots for determining a point on the Nyquist plot at frequency ω_p

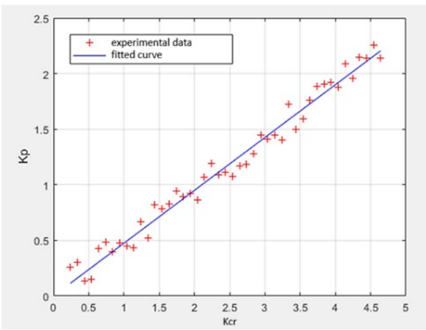

Figure 3. Dependence of the controller gain on the critical point

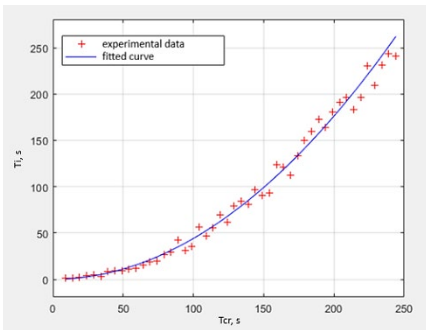

Figure 4. Dependence of the controller integral time constant on the critical point

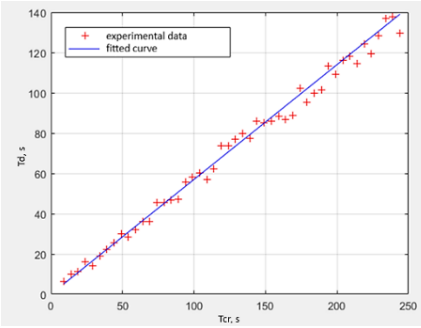

Figure 5. Dependence of the controller derivative time constant on the critical point

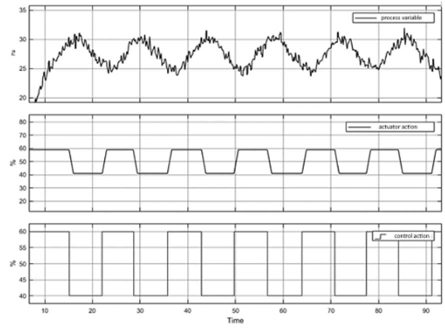

Figure 6. Transient processes during PID controller auto-tuning of the boiler furnace draft control system

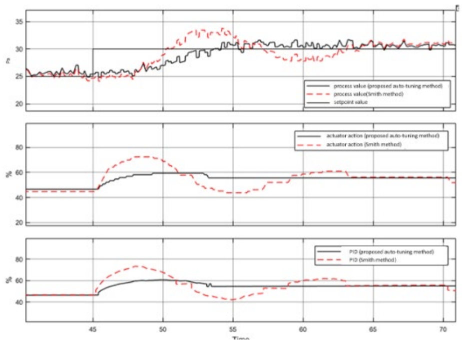

Figure 7. Transient processes of the boiler furnace draft automatic control system