Journal of Engineering and Technology for Industrial Applications

ITEGAM-JETIA

Manaus, v10. n.50, p. 10-16. November./ December., 2024.
DOI: https://doi.org/10.5935/jetia.v10i50.1265

ISSN ONLINE: 2447-0228

RESEARCH ARTICLE

OPEN ACCESS

A NEW PID TYPE CONTROLLER BASED ON MODIFIED CRISP LOGIC

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ARTICLE INFO

Article History
Received: August 24, 2024
Revised: October 16, 2024
Accepted: November 1, 2024
Published: November 30, 2024

Keywords:
Fuzzy Logic control,
Modified crisp logic,
PID, Self-tuning
Relative Rate Observer.

ABSTRACT

A PID type fuzzy logic controller (FLC) is a control scheme that utilizes fuzzy inference systems to replicate the behavior of a classical PID controller. This approach provides an alternative for systems where traditional PID control encounters difficulties, particularly in scenarios involving human expertise or non-linear behavior. In this study, we propose a novel PID-like controller that employs a modified crisp logic method—a rule-based approach designed to implement the reasoning process. This method aims to reduce processing time in fuzzy inference systems by using crisp sets instead of fuzzy sets and simple calculations to generate the output. Simulation results demonstrate the effectiveness of the proposed method, achieving comparable performance with the added benefit of reduced processing time.

I. INTRODUCTION

Fuzzy logic, introduced by Lotfi Zadeh in 1965, is a computational approach that allows for approximate reasoning, mimicking human decision-making processes [1]. Unlike traditional Boolean logic, where variables are strictly true or false, fuzzy logic employs membership functions to represent degrees of truth, with values between 0 and 1. This flexibility makes it particularly useful for handling uncertainty and ambiguity prevalent in real-world systems. Fuzzy logic control (FLC) is a direct application of fuzzy logic to control systems [2]. It allows us to incorporate human-like reasoning into control strategies. While it may not provide precise reasoning, it offers acceptable reasoning. Additionally, FLC can emulate deductive thinking, similar to how people infer conclusions from what they know. By using a set of linguistic rules and membership functions, FLC models the behavior of systems in a way that mimics human decision-making, providing robust and adaptive control solutions.

A PID type fuzzy logic controller combines the benefits of both PID control and fuzzy logic, resulting in a robust and adaptive control strategy. By utilizing fuzzy rules and membership functions, it effectively manages complex systems characterized by nonlinearities or uncertainties.

In the work by M. Mizumoto [3], the application of fuzzy logic to implement PID control strategies was explored. The study demonstrated that PID controllers can indeed be realized through specific fuzzy control methods, such as the “product-sum-gravity” and “simplified fuzzy reasoning” methods. Consequently, PID control is considered a special case within the broader context of fuzzy control. Notably, the min-max-gravity method lacks the ability to achieve PID controller functionality.

The PID type fuzzy logic controller (FLC) was extensively studied in the literature. The study in [4] presents a comprehensive exploration of crisp-type fuzzy controllers, delving into their fundamental principles, their basic structures, and operational characteristics. By conducting an in-depth analysis of their behavior, the unique attributes differentiating them from traditional fuzzy controllers are highlighted. Moreover, the chapter investigates strategies to optimize controller performance, focusing on enhancing efficiency and effectiveness in complex control scenarios. Through comparative studies and simulation-based evaluations, the potential benefits and real-world applications of crisp-type fuzzy controllers are demonstrated. The paper by Xu, Hang, and Liu introduces a novel approach to fuzzy PID control by employing a parallel structure [5]. This design involves combining independent fuzzy proportional and derivative controllers, offering increased flexibility and potential for improved performance compared to traditional fuzzy PID controllers. A key contribution of this work is the development of a tuning method based on gain and phase margins, facilitating controller design and optimization. In contrast to the complex rule-based structures often associated with fuzzy controllers, this research explores a simplified architecture with a reduced number of fuzzy sets. This streamlined approach enhances computational efficiency and enables stability analysis. By focusing on the core components of PID control, the authors demonstrate the effectiveness of this simplified fuzzy PID controller in achieving desired control objectives.

Parameter self-tuning is crucial for PID controllers to maintain optimal performance in dynamic environments by automatically adjusting control parameters to adapt to changing system conditions. The authors of [6] use Parameter Adaptive Method for real-time adjustment of PID parameters. The approach adopted in [7] introduce a novel PID type fuzzy controller that incorporates self-tuning scaling factors. This approach dynamically adjusts the proportional, integral, and derivative gains through a fuzzy inference system. By adapting to changing system conditions, the controller enhances performance and robustness. The authors demonstrate the controller's effectiveness through simulations and practical applications. Reference [8] proposes a novel self-tuning method for PID-type fuzzy logic controllers. By employing a relative rate observer to estimate system dynamics, the controller adaptively adjusts its scaling factors. This approach enhances the controller's ability to handle varying operating conditions and improve overall performance. This approach was implemented on a PLC [9] and compared with other self-tuning mechanisms in [10]. This methos was also used in a number of applications [11-16]. The self-tuning of different PID type fuzzy controllers was studied in literature [17-21].

Modified crisp logic is a simplified approach to fuzzy logic that aims to reduce computational complexity while retaining some of the benefits of fuzzy reasoning [22]. Unlike traditional fuzzy logic, which uses membership functions to represent degrees of truth, modified crisp logic employs crisp sets with defined thresholds. Essentially, it's a hybrid method that combines elements of both crisp logic and fuzzy logic. By simplifying the fuzzy inference process, modified crisp logic can potentially improve computational efficiency without sacrificing too much control performance. The main objective of this study is to use the modified crisp logic method to implement the PID type controller and the self-tuning mechanism.

The remainder of this paper is structured as follows. Section 2 provides a brief overview of PID type FLC. In Section 3, the principles of modified crisp logic are elaborated. Section 4 delves into the proposed self-tuning methods. Simulation results and their analysis are presented in Section 5. Finally, Section 6 summarizes the key findings and outlines potential directions for future research.

II. PID TYPE FLC

Figure 1 illustrates a typical closed-loop control system incorporating a standard PID type FLC [8]. The control signal generated by the PID type FLC is determined by:

$$u = \alpha U + \beta \int U dt \tag{1}$$

where U is the output of the FLC bloc.

Previous research [6] has demonstrated that fuzzy controllers employing product-sum inference, center of gravity defuzzification, and triangular input membership functions with a crisp output exhibit an input-output relationship defined by:

$$U = A + PE + D\dot{E} \tag{2}$$

Where $E = K_e e$ and $\dot{E} = K_d \dot{e}$.

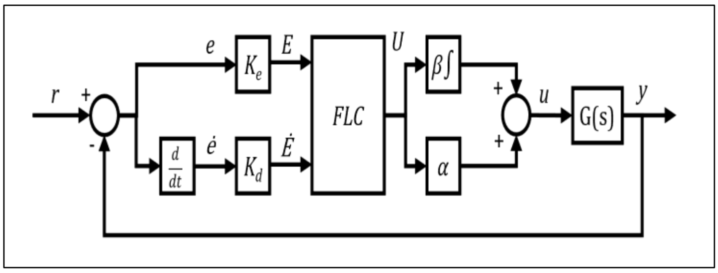

Figure 1: Closed-loop control structure for PID type FLC.
Source: Authors (2024).

Consistent findings in [23],[24] confirm that the minimum inference engine also produces the same input-output relationship. Combining equations (1) and (2) yields the controller output as follows:

$$u = \alpha A + \beta At + \alpha K_e Pe + \beta K_d De + \beta K_e P \int edt + \alpha K_d D\dot{e} \tag{3}$$

Consequently, the equivalent PID type FLC control components are derived as follows:

Proportional gain: $\alpha K_e P \beta K_d D$
Integral gain: $\beta K_e P$
Derivative gain: $\alpha K_d D$.

III. MODIFIED CRISP LOGIC

To streamline the fuzzy control process, modified crisp logic introduces two key modifications [22]. Firstly, crisp, non-overlapping membership functions are adopted for input variables. This simplification eliminates the need for complex membership degree calculations and rule inference, as each input belongs exclusively to one crisp set. Consequently, output sets are defined as singletons, thereby obviating the defuzzification stage. Secondly, to mitigate the potential abrupt transitions caused by crisp set-based outputs, a smoothing function is applied to generate the final control signal. This function effectively attenuates the discontinuous nature of the output, enhancing overall system performance. By incorporating these enhancements, the proposed controller offers a computationally efficient and robust alternative to fuzzy control.

The output value in the case of a system with 2 inputs and a single output is given by the following equation:

$$u = rule(i,j) - \frac{\Delta a + \Delta b}{2} \tag{4}$$

Here, rule (i,j) is a singleton output associated with the combination of input values belonging to crisp sets i and j, respectively.

$$\Delta a = c_a(i) - a \tag{5}$$

$$\Delta b = c_b(j) - b \quad (6)$$

Where a and b denote the input variables. The centers of the crisp sets corresponding to a and b are represented by ca(i) and cb(j), respectively. The difference between inputs (a, b) and their associated crisp sets are denoted by Δa and Δb.

The proposed controller architecture, illustrated in Figure 2, eliminates the need for fuzzification, complex fuzzy inference and defuzzification processes. By directly mapping input crisp sets to output singleton values, the controller significantly reduces computational burden. This streamlined approach enables real-time implementation without requiring specialized software or hardware.

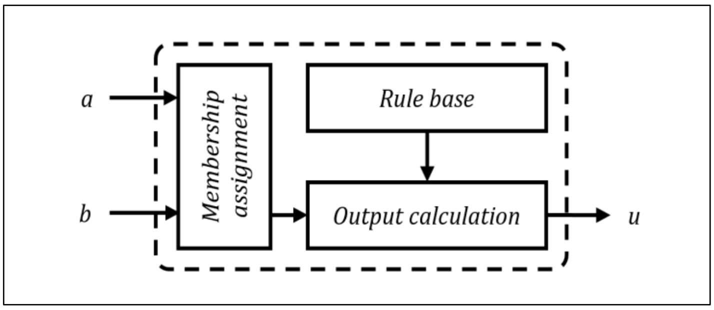

Figure 2: The architecture of the modified crisp logic controller.
Source: Authors (2024).

IV. MODIFIED CRISP LOGIC PID TYPE CONTROLLER

The proposed PID type controller shares the same architectural framework as its fuzzy counterpart (Figure 1), with the exception of the inference system, which is based on modified crisp logic. The conventional FLC block is replaced by a crisp logic equivalent as illustrated in Figure 2. For comparison, a standard PID type FLC utilizes the membership functions depicted in Figure 3(a), while the proposed PID employs those shown in Figure 3(b). The distinct characteristics of these membership functions are evident.

The rule base presented in Table 1 governs both the FLC inference process and the output calculation for the proposed controller.

Table 1: Rule base.

Ė/E	N	P
N	N	Z
P	Z	P

Source: Authors (2024).

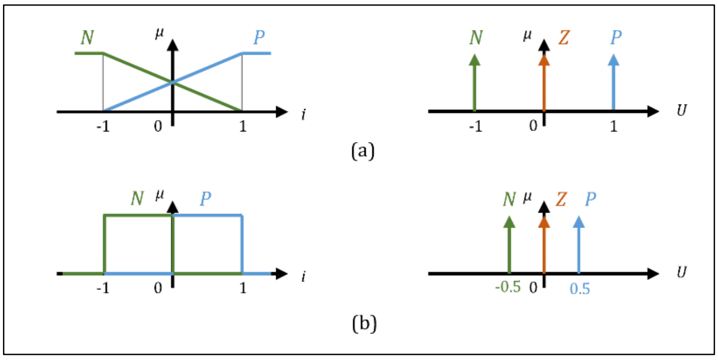

Figure 3: Membership functions (a) FLC, (b) Modified crisp logic.
Source: Authors (2024).

The control surfaces for both controllers are illustrated in Figure 4. Both methods yield identical decision surfaces. The FLC uses the product–sum inference mechanism and center of gravity defuzzification method.

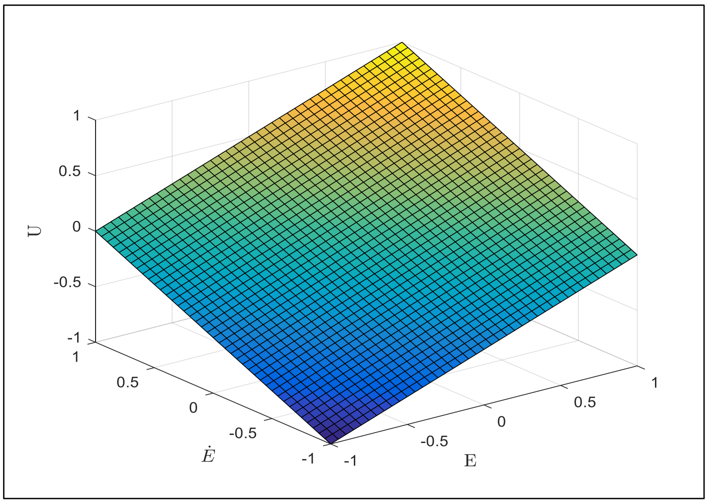

Figure 4: Control surface.
Source: Authors (2024).

V. SELF-TUNING OF A PID TYPE FLC

Numerous self-tuning strategies have been proposed to optimize PID type fuzzy logic controller parameters. One such approach is peak observer-based parameter adaptation, which leverages system peak responses to adjust controller settings in real-time [6]. By extracting information from these peaks, the method refines fuzzy controller scaling factors or membership functions. Alternatively, function tuners offer a more flexible approach, employing mathematical functions to correlate system behavior with desired parameter adjustments [23].

This paper focuses on the relative rate observer (RRO) method, which estimates system parameters based on output rate variations [8]. The architecture of PID type FLC with RRO self-tuning is illustrated in Figure 5. The proposed method leverages both system error and rate information to optimize PID type FLC performance. A fuzzy inference mechanism dynamically adjusts scaling factors associated with the derivative and integral coefficients. This mechanism employs two inputs: system error (e) and normalized acceleration (rv), as defined in [8]. The latter provides insights into system response dynamics, effectively functioning as a relative rate observer (RRO). The normalized acceleration rv(k) can be defined as:

$$r_v(k) = \frac{\ddot{e}(k)}{\dot{e}(\cdot)} \quad (7)$$

Where $\dot{e}(\cdot)$ is chosen as follows:

$$\dot{e}(\cdot) = \begin{cases} \dot{e}(k) & if\ |\dot{e}(k)| \geq |\dot{e}(k-1)| \\ \dot{e}(k-1) & if\ |\dot{e}(k)| < |\dot{e}(k-1)| \end{cases} \quad (8)$$

The fuzzy parameter regulator generates an output denoted as γ. The scaling factor for the derivative term, Kd, is modified by multiplying its initial value with γ. Conversely, the scaling factor for the integral term, β, is adjusted by dividing its initial value by γ.

$$K_d = K_{ds} K_{fd} K_f \gamma \tag{9}$$

$$\beta = \frac{\beta_s}{K_f \gamma} \tag{10}$$

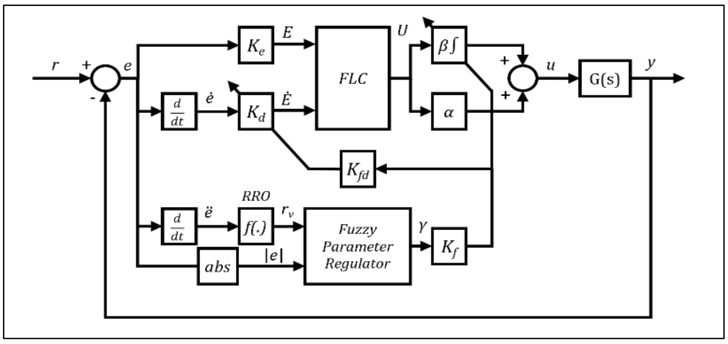

Figure 5: PID type FLC using RRO.
Source: Authors (2024).

Figure 6 and Figure 7 depict the input membership functions for the fuzzy and crisp modules respectively. It's important to note that output membership functions are singletons, specified within the corresponding rule tables.

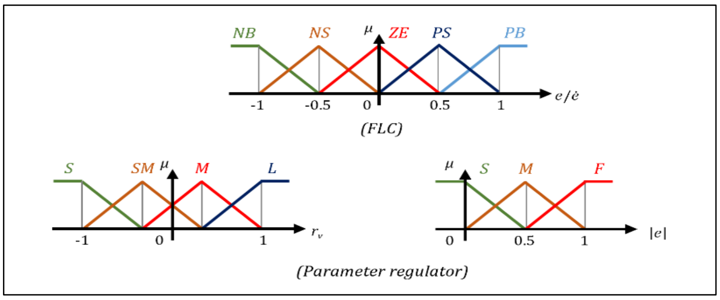

Figure 6: Membership functions for the fuzzy PID.
Source: Authors (2024).

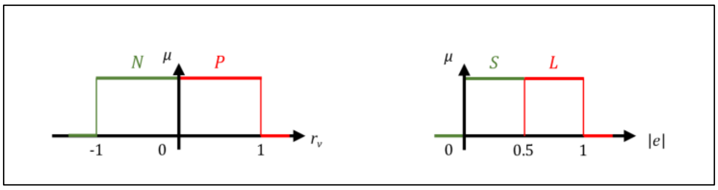

Figure 7: Membership functions for the crisp Parameter regulator.
Source: Authors (2024).

The symmetrical rule base outlined in [6] is presented in Table 3. This rule base serves as the foundation for the PID type FLC. The linguistic terms assigned to the input variables, error (E) and change in error (Ė), are: Negative Big (NB), Negative Small (NS), Zero (ZE), Positive Small (PS), and Positive Big (PB). The rule base for the crisp PID controller is the one presented in Table 1. Given that two crisp sets are employed for the input variables, the rule base is structured as a 2x2 matrix.

Table 2: Rule base of the fuzzy PID.

Ė/E	**NB**	**NS**	**ZE**	**PS**	**PB**
NB	-1	-0.7	-0.5	-0.3	0
NS	-0.7	-0.4	-0.2	0	0.3
ZE	-0.5	-0.2	0	0.2	0.5
PS	-0.3	0	0.2	0.4	0.7
PB	0	0.3	0.5	0.7	1

Source: Authors (2024).

Table 4 presents the rule base for the fuzzy parameter regulator [8]. The linguistic terms for the input variable $|e|$ and the output variable g are: Large (L), Small (S), Medium (M), and Small Medium (SM). For the other input variable, rv, the linguistic terms are: Fast (F), Moderate (M), and Slow (S). While Table 4 presents the rule base of the crisp parameter regulator.

Table 3: Rule base of the fuzzy parameter regulator.

$|e|$ **/**r_v	**S**	**M**	**F**
S	M	M	L
SM	SM	M	L
M	S	SM	M
L	S	S	SM

Source: Authors (2024).

Table 4: Rule base of the crisp parameter regulator.

$|e|$ **/**r_v	**N**	**P**
S	0.5	0.75
L	0.25	0.5

Source: Authors (2024).

VI. RESULTS AND DISCUSSION

In [8], the authors conducted a comparative analysis of the RRO method against conventional PID, peak observer, and function tuner approaches. The RRO method demonstrated superior efficiency due to its reduced parameter tuning requirements and enhanced robustness to system variations compared to its counterparts.

This section presents a comparative analysis of the proposed self-tuned PID controller based on modified crisp logic and a PID type FLC equipped with an RRO. Simulation studies were conducted on a second-order linear system characterized by varying parameters and transport delay defined by:

$$G_p(s) = \frac{K e^{-T_D s}}{s^2 + Ps + Q} \tag{11}$$

Discrete simulation with a sampling period of Ts = 0.1 s was employed for the experiments. Nominal system parameters were set as K = 16, P = 3, Q = 2, and TD = 0. To ensure consistency, parameters a = 0.2, b = 1, Ke = 0.8, and Kd = 0.25 remained constant for both controllers.

Two types of tests were performed: one-parameter and two-parameter adjustments. For the one-parameter case, the optimal value of Kf was found to be 4.35 while maintaining Kfd at 1. In the two-parameter adjustment scenario, Kf and Kfd were optimized to 1.9 and 2.45, respectively.

Figure 8 demonstrates that the proposed method with single-parameter adjustment yields a satisfactory response, comparable to the fuzzy PID with RRO. Figure 10 illustrates that simultaneous adjustment of both Kfd and Kf parameters results in an improved response. Figs. 9 and 11 present the control efforts exerted by both controllers. Notably, the crisp controller generates a smoother control signal with lower magnitude compared to the fuzzy controller.

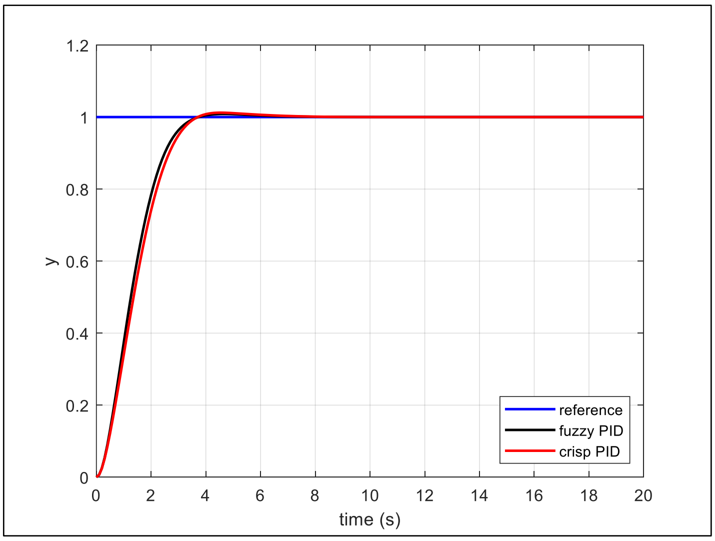

Figure 8: Unit step responses for the nominal system with one parameter adjustment.
Source: Authors (2024).

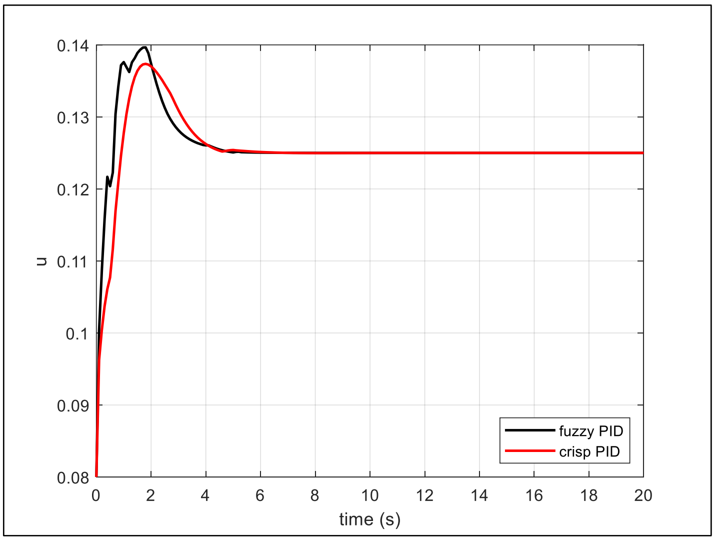

Figure 9: Control effort with one parameter adjustment.
Source: Authors (2024).

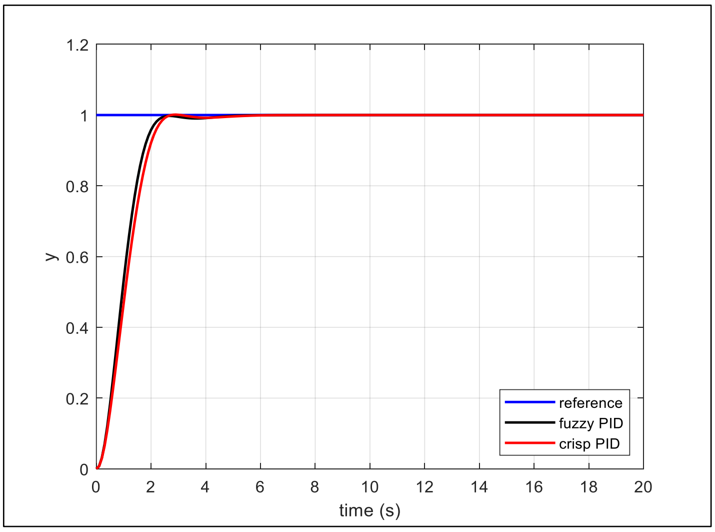

Figure 10: Unit step responses for the nominal system with two parameters adjustment.
Source: Authors (2024).

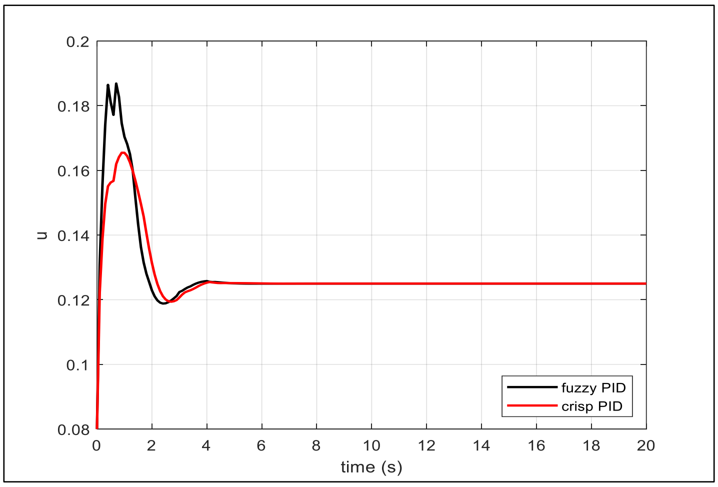

Figure 11: Control effort with two parameters adjustment.
Source: Authors (2024).

To evaluate and compare the proposed methods, a simulation study was conducted under varying system conditions. The plant transfer function denominator coefficients, P and Q, were systematically varied within the range of 0 to 4 without anytime delay, ensuring system stability by limiting pole locations to a left-half plane circle with a radius of 2. Four representative system configurations, labeled a to d, were examined. Specific parameter values and corresponding system types for each case are provided as follows:

Case a: $P = 2$ and $Q = 1$; overdamped stable system.
Case b: $P = 2$ and $Q = 0$; marginally stable system.
Case c: $P = 2$ and $Q = 2$; underdamped stable system.
Case d: $P = 0.5$ and $Q = 4$; almost oscillatory system.

For the remaining simulations, controller parameters were fixed at the optimal values determined for the nominal system. System responses for cases a to d are depicted in Figs. 12 to 15, respectively. Only the results for two parameter adjustments are presented. When at least one open-loop plant pole is located close to the imaginary axis, as in cases b and d. The PID type crisp controller demonstrates superior performance compared to the PID type fuzzy controller. To assess the impact of time delay, a 0.25s delay was introduced to the nominal system while maintaining fixed controller parameters. Figure 16 presents the resulting unit step responses for the compared methods. The crisp PID with two-parameter adjustment consistently outperforms the fuzzy PID controller under these conditions.

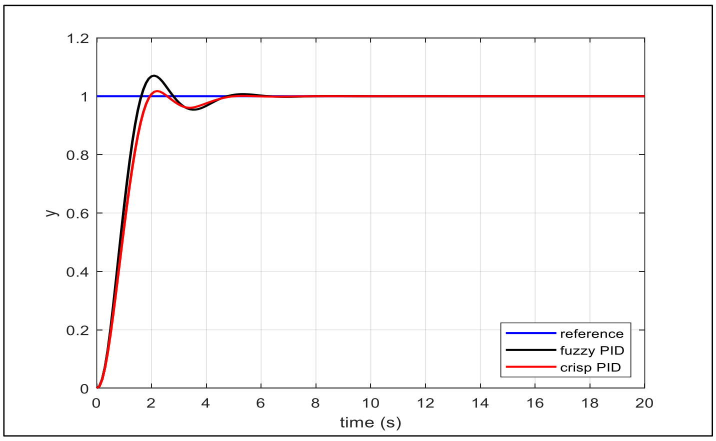

Figure 12: Unit step responses for case a.
Source: Authors (2024).

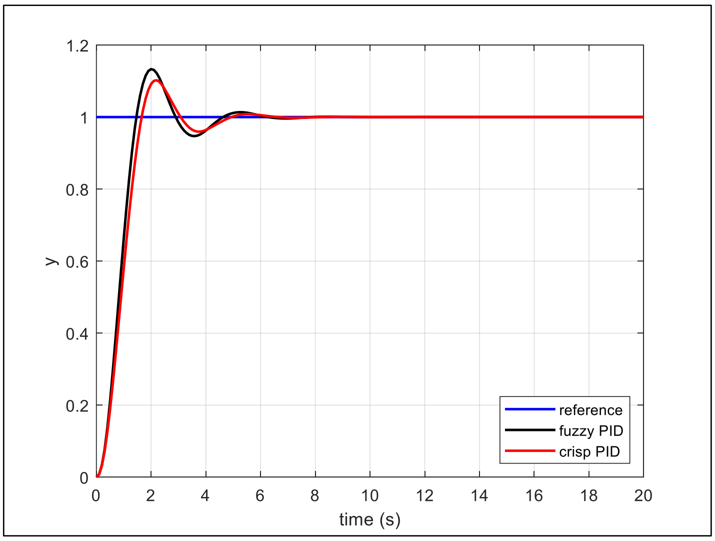

Figure 13: Unit step responses for case b.
Source: Authors (2024).

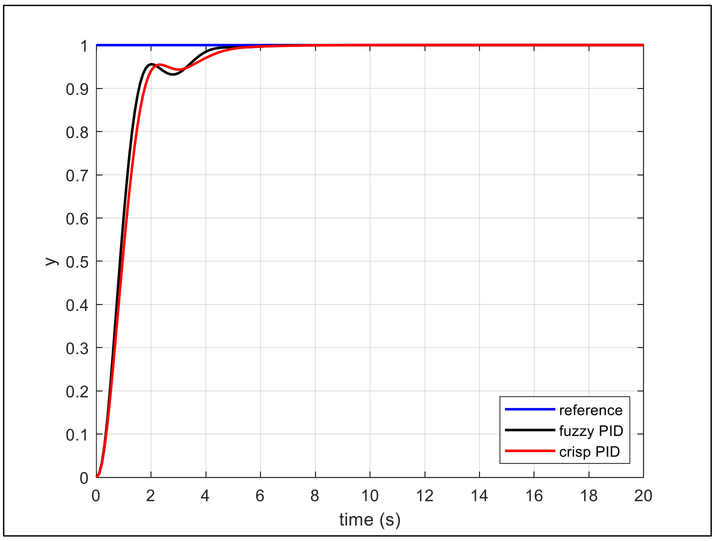

Figure 14: Unit step responses for case c.
Source: Authors (2024).

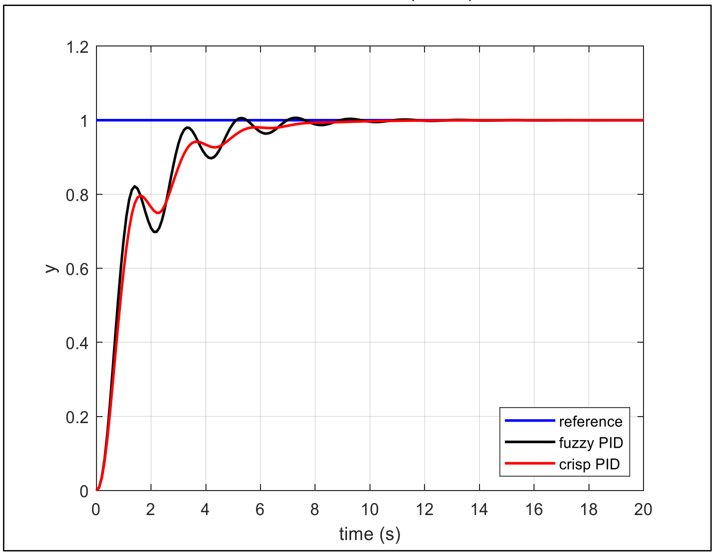

Figure 15: Unit step responses for case d.
Source: Authors (2024).

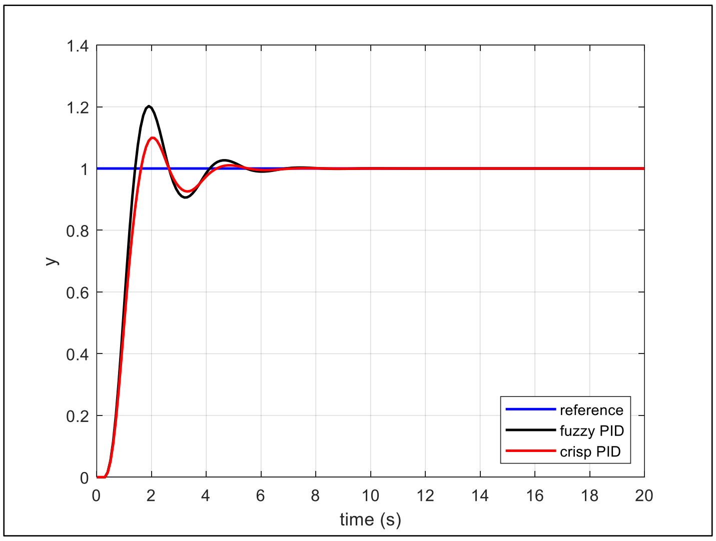

Figure 16: Unit step responses with TD = 0.25 s.
Source: Authors (2024).

VII. CONCLUSIONS

This research has successfully implemented a PID type controller utilizing modified crisp logic and a relative rate observer self-tuning mechanism. By simplifying the fuzzy inference process through crisp set theory, computational efficiency was significantly enhanced without compromising performance.

The proposed controller, while sharing a similar architecture with its fuzzy counterpart, demonstrated superior performance in terms of robustness and adaptability to system variations. Simulation results confirmed the effectiveness of the approach in handling complex system dynamics.

Future research will focus on applying this controller to more challenging and complex real-world applications.

VIII. AUTHOR'S CONTRIBUTION

Conceptualization: Abdeslam Benmakhlouf, Ghania Zidani and Djalal Djarah.
Methodology: Abdeslam Benmakhlouf and Ghania Zidani.
Investigation: Abdeslam Benmakhlouf and Ghania Zidani.
Discussion of results: Abdeslam Benmakhlouf, Ghania Zidani and Djalal Djarah.
Writing – Original Draft: Abdeslam Benmakhlouf.
Writing – Review and Editing: Ghania Zidani and Djalal Djarah.
Resources: Ghania Zidani.
Supervision: Djalal Djarah.
Approval of the final text: Abdeslam Benmakhlouf, Ghania Zidani and Djalal Djarah.

IX. DISCLAIMER

The authors declare that they received no financial support or grants from any public, commercial, or non-profit entities for this research. All the views expressed in this work are solely those of the authors.

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