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Research Article

# A Novel PI-PD Controller Tuning Method Based on Neutrosophic Similarity Measure for Unstable and Integrating Processes with Time Delay

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ABSTRACT

Integrating systems and unstable systems are two types of systems that are widely used in various industries, including control engineering and electrical engineering. However, controlling these systems can be a daunting task due to their inherent complexity. To address this challenge, the PI-PD controller structure has been widely adopted in the industry, as it has proven to be very successful in controlling integrating and unstable systems. In this paper, a new design method is proposed to determine the optimal controller parameters in the control of integrating and unstable systems with time delay. The design method utilizes a Genetic Algorithm-based optimization technique, which incorporates a new objective function that is based on the neutrosophic similarity measure. Two different types of plants have been chosen as examples in this study. The first plant is a time-delayed integrating system. The second plant is an unstable system, which means the output signal is susceptible to changes or disturbances in the input signal. This study examines the parameter uncertainties of systems by comparing them with some design methods from the literature. The results are presented comparatively in figures and tables to show the superiority of the proposed method.

## Introduction

Unstable and integrating processes with time delay are common types of systems that require special attention when designing a control strategy. Unstable processes have a tendency to oscillate uncontrollably while integrating processes have a slow response to changes in the input. Time delay in a process can exacerbate these issues, as it can introduce additional instability and oscillation. Most industrial processes are characterized by time delay [1]. It is important to model these time delays accurately, as they can have significant impacts on the performance of the system over time. Transfer functions with time delay are particularly useful in modeling physical systems, as time delay is a common feature in many real-world systems [2]. Industrial processes such as heating boilers, level control, stirred tank reactors, paper drum dryer, and boiler steam drums are integrating and unstable systems. Since such systems contain poles at the origin and right half of the complex plane, these systems are very difficult to control [3, 4].

Advanced control techniques, including model-based predictive control, adaptive control, or robust control, are often required to effectively regulate unstable and integrating processes with time delay. These techniques are designed to account for the complex dynamics of the system and provide stable and robust control in the presence of time delay. Conventional controllers, such as PID (Proportional Integral Derivative) controllers, can be used when there is dead time, but they perform poorly [5]. Also, it is known that the PID controller is insufficient to control unstable and integrating processes. Although PI-PD (Proportional Integral - Proportional Derivative) controllers are similar to PID controllers, they differ in some points. For example, while PID controllers have some structural limitations in providing the desired performance in the control of unstable, integrating and resonant systems, PI-PD controllers offer very good results for such systems [6]. While PID controllers have three parameters to be set, the PI-PD controller has four parameters in its structure. The PI-PD tuning method is a type of controller tuning method that is designed to achieve stable and robust control of integrating and unstable systems with time delay. This method combines both PI and PD control action to achieve improved performance. The PI part of the controller helps to address steady-state errors in the system by integrating the error signal over time and adjusting the control output accordingly. The PD part of the controller helps to address the dynamic response of the system by introducing a derivative term that is proportional to the rate of change of the error signal. This derivative term helps to improve the response speed of the controller. The PD controller improves the transfer function and response of the system through the feedback loop. Thus, the poles are better positioned according to the new transfer function of the obtained system. Then, in the second loop with the PI controller, it is tried to reach the desired level of system performance. The addition of PD feedback in the inner loop can transform an open-loop unstable system into an open-loop stable one [6]. This is achieved by designing the feedback such that the output of the system converges to a desired set point. Furthermore, the proper position of stable open-loop poles is provided, meaning that the system is designed to have a stable response, even in the absence of feedback. This ensures that the system can handle external disturbances and can quickly return to a stable state after a disturbance. In this respect, the PI-PD controller structure is more advantageous than conventional PID controllers. PI-PD controllers are a control structure that provides very good results in the control of stable, unstable, integrating and resonant processes. Thus, obtaining the controller parameters for these controllers is crucial to achieve system stability. There are many precious studies on this topic in the literature [7-10]. Obtaining the most suitable parameters in the determination of controller parameters is a very serious problem and studies are still continuing on new methods.

To achieve the expected performance characteristics of a control system, it is important to tune the controller parameters. The extensive utilization of PID controllers has prompted numerous researchers to develop alternative design techniques for these controllers. The Ziegler-Nichols [11] and Åström-Hägglund [12] methods are two of the most well-known and oldest methods for determining the controller parameters of classical PID controllers. These methods have been widely used in industry and academia for many years and are still commonly used today due to their simplicity and ease of implementation. The Ziegler-Nichols method is a heuristic method that involves applying a step input to the system and adjusting the controller parameters until the system oscillates at a constant amplitude. The parameters are then determined based on the oscillation frequency and amplitude. The Åström-Hägglund method is a more systematic method that involves optimizing the controller parameters based on the system's step response characteristics. While the Ziegler-Nichols and Åström-Hägglund methods are effective for determining the controller parameters of classical PID controllers, they may not always provide optimal performance for more complex systems with non-linear dynamics and time delays. In such cases, more advanced control design methods, such as model-based and optimal control methods, may be required. In addition to PID tuning methods such as Cohen-Coon, Wang-Juang-Chan, methods based on pole placement, gain-phase margin, frequency analysis, stability analysis, and determination of optimal controller parameters are also used [13]. Optimization methods are effective methods that are based on the minimization of the error signal and are frequently used in the determination of control parameters. Performance criteria that incorporate the integral of the error signal have been developed to compute the optimal controller parameters, taking into account the error in the closed-loop control system [14]. For example, Zhuang and Atherton [15] obtained the PID controller parameters using integral performance criteria. In their study, they presented new information about integral performance criteria and explained how they were included in the MATLAB program. Padulo and Visioli [16], who presented a set of parameter setting rules for integer and fractional order PID controllers, determined the controller parameters by minimizing with the integral of the absolute of the error (IAE) performance criterion for systems with different structures. Deniz et al. [17] determined the fractional order PID controller parameters based on ISE, ISTE, and $IST^2E$ performance criteria. Works such as [18-20] can also be given as examples of this topic. Furthermore, the optimal controller parameters can be determined by minimizing an objective function, which is defined based on the system output according to the design criteria. For example, Jun Ye [21] has proposed a method for determining PID controller parameters using GA (Genetic Algorithm) by describing an advanced level of fuzzy logic, a neutrosophic logic-based objective function. In a similar study, Fu et al. [22] used the method proposed by [21] to determination the neutrosophic self-tuning PID controller parameters for speed control of an AC permanent magnet synchronous motor.

With the understanding that the PI-PD controller provides superior control performance in many industrial processes, the number of studies involving this controller has increased rapidly. For example, Ozyetkin et al. [23] developed a straightforward and effective PI-PD tuning approach for time-delayed systems. The method is based on the determination of the stability regions of the PD and PI controller parameters by the stability boundary locus method. Then, the controller parameters are determined by the weighted geometric center method within this stable region. The researchers highlighted that their method produced reliable and robust results. Raja and Ali [4] put forward a novel method for tuning PI-PD controllers designed for unstable and integrating systems with time delay. The controller parameters were determined through the application of moment-matching technique and Routh-Hurwitz stability criteria. Another study [24] introduced a graphical technique utilizing the stability boundary locus to regulate time-delay unstable systems with a PI-PD controller. To demonstrate the effectiveness of this method, the researchers provided simulation examples and an experimental application in their study. Padhy and Majhi [25] suggested a design for a relay-based PI-PD controller that can be used for stable, unstable, and time-delayed systems. According to their findings, this approach is straightforward and enhances the performance of PI-PD controllers in comparison to various other methods. It is possible to reproduce similar works [26, 27].

The objective of this research is to develop a new PI-PD tuning method that can effectively control integrating and unstable systems with time delay while taking into account desired design criteria to improve control performance. To achieve this objective, the researcher proposes a GA optimization approach that uses a novel objective function based on the neutrosophic similarity measure to determine the PI-PD controller parameters. The effectiveness of the proposed method is evaluated by integrating and unstable systems with time delay, and its performance is compared with other studies in the literature under different conditions such as disturbances input and parameter changes. The results indicate that the proposed method yields successful control performance, demonstrating its efficacy in controlling such systems.

The paper is divided into several sections. The second section provides an introduction to the neutrosophic similarity measure. Section 3 concentrates on tuning PI-PD controller parameters, beginning with a discussion of the PI-PD controller structure and optimization method employed in the study. Section 4 demonstrates the practical application of the proposed method by presenting two simulation examples, and comparing the results to those of previous studies in the literature. Finally, the last section outlines the research's findings.

## Neutrosophic Logic and Neutrosophic Similarity Measure

Smarandache proposed the concept of neutrosophy, which is a generalized form of intuitionistic fuzzy logic, and neutrosophic sets based on this concept [28-31]. In this approach, a phenomenon is fuzzified by using membership values with three different values called True ($T$), Indeterminate ($I$) and False ($F$), unlike Fuzzy logic. Known set operators such as union and intersection used in fuzzy set theories are performed by considering these three membership values [31]. For example, the value $T$ represents the degree of occurrence of an event, $F$ is the degree of non-occurrence, and $I$ the degree of uncertainty in the case of occurrence. Some basic definitions for neutrosophic logic are given below.

**Definition 1:** The universal set $X$ is defined as the set of all elements. An arbitrary element in this set is represented by the symbol $x$. a neutrosophic set $A$ in the universal set $X$ is then characterized by three membership functions [31]:

1. The truth-membership function, denoted as $T_A(x)$, assigns a degree of membership to $x$ in the truth subset of $A$.
2. The indeterminacy-membership function, denoted as $I_A(x)$, assigns a degree of membership to $x$ in the indeterminate subset of $A$.
3. The falsity-membership function, denoted as $F_A(x)$, assigns a degree of membership to $x$ in the falsity subset of $A$.

They presented examples of single-valued neutrosophic sets (SVNS) suitable for use in real scientific and engineering applications [32]. The following definitions are for subsets $A$ and $B$, which are SVNS in the $X$ universal set. These definitions apply to all $x$ elements in the universal set $X$.

**Definition 2:** The complement $c(A)$ of a SVNS set $A$ in the universal set $X$ is defined as follows [32];

$T_{c(A)}(x) = F_A(x)$,

$I_{c(A)}(x) = 1 - I_A(x)$,

$F_{c(A)}(x) = T_A(x)$

**Definition 3 (Union):** The union of two SVNS, designated $A$ and $B$, is again an SVNS. The process $C = A \cup B$ is defined as follows [32];

$T_{c(A)}(x) = max(T_A(x), T_B(x))$,

$I_{c(A)}(x) = max(I_A(x), I_B(x))$,

$F_{c(A)}(x) = min(F_A(x), F_B(x))$

**Definition 4 (Intersection):** The intersection of the two SVNS, indicated by $A$ and $B$, is again an SVNS. The $C = A \cap B$ operation is defined as follows [32]**;**

$T_{c(A)}(x) = min\ (T_A(x), T_B(x))$,

$I_{c(A)}(x) = min\ (I_A(x), I_B(x))$,

$F_{c(A)}(x) = max(F_A(x), F_B(x))$

**Definition 5 (Containment):** $A$ being an SVNS, if and only if the other $B$ SVNS is present under the following conditions ($A \subseteq B$) [32]**;**

$T_A(x) \leq T_B(x)$,

$I_A(x) \leq I_B(x)$,

$F_A(x) \leq F_B(x)$

**Definition 6:** SVNS $A$ and SVNS $B$ are equal sets if and only if $A \subseteq B$ and $B \subseteq A$ ($A = B$) [32].

The similarity measure (SM) is a method used to determine the degree of similarity between two or more data sets. It is a mathematical technique that helps to compare the similarity or dissimilarities between data points. SM can be used to compare various types of data sets, such as numerical, categorical, or even text data. The function of SM is to quantify the similarity between the data, which helps in better decision-making and problem-solving. Sets defined according to certain criteria can be used as data sets. In this way, the degree of similarity between two or more sets can be determined by this method. This approach is a widely used method in decision-making problems [33]. Further, this method is widely used in various fields, including machine learning, data mining, and image processing. By using the SM, we can quantify the similarity between datasets and use this information to make informed decisions. A similarity measure between sets defined in neutrosophic space is proposed in [34].

In control applications, it is one of the main goals for a system to reach the control reference in the shortest possible time and with the least oscillation and to stay at this reference value. Further, the minimum overshoot value should be obtained. The process of tuning the PID controller parameters is geared towards meeting as many of these specifications as possible. The process of determining the optimal values of the PID parameters is actually a decision-making problem [33]. In recent years, studies have been carried out in the literature to determine PID controller parameters using the neutrosophic similarity measure [21, 22, 33]. In these studies, researchers first determine an ideal neutrosophic set consisting of as many elements as the number of unit-step characters for the requested unit-step response (rise time, maximum overshoot, settling time, peak time, etc.) of the controlled system. While determining the ideal set, as a general approach, it can be chosen to take the *T* value close to 1 and the *F* and *I* values close to 0. Then, each of the unit step characteristics taken from the system is passed through *T*, *I*, and *F* membership functions, taking into account the system response expectations and general control criteria, so that each unit step criterion is converted to a neutrosophic value in the form of $x\,(T, I, F)$. As a result, the PID controller parameters are determined according to the difference between the ideal set and the real set using the neutrosophic similarity measure.

**Theorem 1:** Let the similarity measure between sets *A* and *B* be denoted as SM(*A*,*B*) [35];

(i) SM(*A*,*B*) = SM(*A*,*B*),

(ii) $0 \leq SM(A,B) \leq 1$,

(iii) SM(*A*,*B*) = 1, if and only if *A* = *B*.

**Definition 7:** $S_J$, $S_D$, $S_C$ are vector similarity measures of Jaccard, Dice, and Cosine, respectively. These are defined as follows [21];

$$S_J(A,B)=\frac{1}{n}\sum_{i=1}^{n}\frac{\begin{pmatrix}T_A(x_i)T_B(x_i)+I_A(x_i)I_B(x_i)\\+F_A(x_i)F_B(x_i)\end{pmatrix}}{\begin{pmatrix}(T_A^2(x_i)+I_A^2(x_i)+F_A^2(x_i))+\\(T_B^2(x_i)+I_B^2(x_i)+F_B^2(x_i))\\-\begin{pmatrix}T_A(x_i)T_B(x_i)+I_A(x_i)I_B(x_i)\\+F_A(x_i)F_B(x_i)\end{pmatrix}\end{pmatrix}} \quad (1)$$

$$S_D(A,B)=\frac{1}{n}\sum_{i=1}^{n}\frac{2\begin{pmatrix}T_A(x_i)T_B(x_i)+I_A(x_i)I_B(x_i)\\+F_A(x_i)F_B(x_i)\end{pmatrix}}{\begin{pmatrix}(T_A^2(x_i)+I_A^2(x_i)+F_A^2(x_i))\\+(T_B^2(x_i)+I_B^2(x_i)+F_B^2(x_i))\end{pmatrix}} \quad (2)$$

$$S_C(A,B)=\frac{1}{n}\sum_{i=1}^{n}\frac{\begin{pmatrix}T_A(x_i)T_B(x_i)+I_A(x_i)I_B(x_i)\\+F_A(x_i)F_B(x_i)\end{pmatrix}}{\sqrt{(T_A^2(x_i)+I_A^2(x_i)+F_A^2(x_i))}\ \mathrm{x}\sqrt{(T_B^2(x_i)+I_B^2(x_i)+F_B^2(x_i))}} \quad (3)$$

**Theorem 2**: The $S_k(A, B)$ similarity measure (where $k = J, D, C$) based on the Jaccard, Dice, and Cosine similarity measures [21] implements the following properties:

(i) $0 \leq S_k(A, B) \leq 1$,

(ii) $S_k(A, B) = S_k(A, B)$,

(iii) $S_k(A, B) = 1$ if $A = B$, i.e., $T_A(x_i) = T_B(x_i)$, $I_A(x_i) = I_B(x_i)$ ve $F_A(x_i) = F_B(x_i)$ all $x_i \in X$.

In the study, Jaccard similarity measure is used in line with the findings of Can and Özgüven [33] in their studies.

## PI-PD Controller Design

Atherton and Majhi [14] propose a modified version of the PID controller (Figure 1) where an internal PD feedback is introduced to relocate the poles of the transfer function to more desirable positions. The modified controller uses a PI controller in the forward loop to improve system performance.

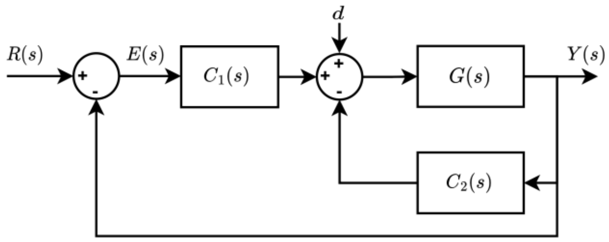



Figure 1. PI-PD feedback control structure.

The PI-PD controller has four parameters to be calculated. The equations of this controller structure are given as follows for the PI and PD controllers, respectively.

$$C_1(s)=K_p+\frac{K_i}{s} \quad (4)$$

$$C_2(s)=K_f+K_d s \quad (5)$$

In the equations, $K_p$ and $K_f$ are the proportional gain, $K_i$ and $K_d$ are the coefficients of the integral and derivative terms, respectively.

In this study, an optimization technique is applied to obtain PI-PD controller parameters. In the optimization technique, the Jaccard neutrosophic similarity measure given in Equation 1 is proposed as the objective function. Thus, it is aimed to contribute to control engineering applications by making an improvement in the PI-PD design methodology. The block diagram of the model used in the design process is given below.

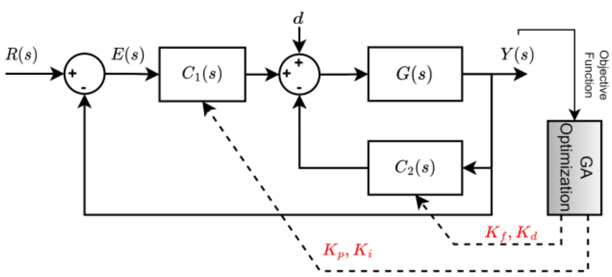



Figure 2. Block diagram of proposed optimization scheme.

In the study, PI-PD controller designs are carried out for two different plant structures, integrating and unstable plants. In the time response of the controlled system, target values of settling, rise, and peak time as well as overshoot and steady-state error are determined. Objective functions using the neutrosophic similarity measure created according to these values are defined. The objective function used in the optimization is given in Equation 6.

$$J_{\min} = 1 - S_J(A,B) \tag{6}$$

In Equation 6, $S_J(A,B)$ is the similarity ratio of $A$ and $B$ single-valued neutrosophic sets. In the equation, set A is the ideal set created for the control performance criteria, and $B$ is the real neutrosophic set created according to the performance criteria taken from the system output. Table 1 shows the ideal neutrosophic set $A$. The representations of $a_i$ given in the table are the neutrosophic elements of the ideal set $A$. For example, the representation of $a_1$ is a 3-valued neutrosophic element obtained by passing the rise time of the system through the neutrosophic membership functions. The neutrosophic representation of this element is $a_i$ ($T_i$, $I_i$, $F_i$).

Table 1. A ideal neutrosophic set.

| *A* | $a_1$ | $a_2$ | $a_3$ | $a_4$ | $a_5$ |
|---|---|---|---|---|---|
| *i* | *Rise time* [1,0,0] | *Settling time* [1,0,0] | *Peak time* [1,0,0] | *O.S (%)* [1,0,0] | *Steady-state error* [1,0,0] |

Each $a_i$ element in the table is obtained with the neutrosophic membership functions shown in Figure 3. These membership functions are determined based on general control criteria and experience. By following the same method, real set $B$ is created.

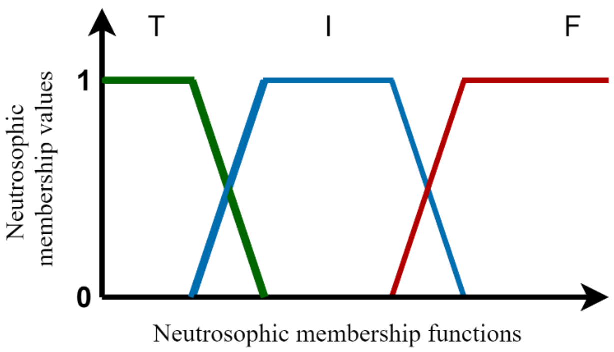



Figure 3. Membership functions used for the unit step response characteristics.

The MATLAB program contains commands and functions in the Optimization toolbox that can be used for minimization or maximization. Genetic algorithm is one of these optimization algorithms. Genetic algorithms, the first general form of which is stated by Goldberg (1989), give more successful results than traditional optimization methods. By scanning a certain part of the solution space, they reach the solution in a short time [36]. Genetic algorithms offer several advantages, such as the ability to optimize complex and non-linear functions, handle constraints on the solution space, search for multiple solutions simultaneously, and avoid getting stuck in local optima, which makes them applicable to a wide range of problems. In the study, GA is used to determine the PI-PD controller parameters. The population size of the GA is chosen to be 50, the number of iterations 100, and the optimization is repeated 10 times for each sample. Then, the PI-PD controller parameters corresponding to the smallest objective function value are determined as the optimal controller parameters.

The proposed method can be summarized as follows.

*Step 1.* The control scheme is created.

*Step 2.* Desired time response specifications are determined for the sample plant.

*Step 3.* The objective function is defined according to the Jaccard neutrosophic similarity measure.

*Step 4.* Variables such as controller parameter lower and upper bounds, population number, and iteration number are defined in optimization algorithms.

*Step 5.* The optimization algorithm is initiated and when the specified number of iterations is reached, the optimization algorithm stops.

*Step 6.* The best controller parameters are determined.

## Simulation Studies

For the purpose of illustrating the viability of the suggested approach, two PI-PD controller designs are made in this section. One of the example given is time-delay integrating processes, while the other one is time-delayed unstable systems. In the examples, the time response specifications of the systems with controllers are compared with various methods in the literature and the results are shown with figures. In addition, the analyses of the systems are made according to the parameter uncertainties, and the results are given in the text.

**Example 1:** Consider

$$G_1(s) = \frac{e^{-0.2s}}{s(0.1s+1)(s+1.2)} \tag{7}$$

which is an integrating transfer function with time delay. The controller design process begins with the determination of the neutrosophic ideal set according to the definition of the transient and steady-state specifications for the processes. In all examples, $A$ neutrosophic ideal set is taken as in Table 1. The reference maximum values of the transient and steady-state specifications for this example are rise time 1.5s, settling time 4s, peak time 4s, maximum overshoot 5%, and steady-state error 0.005. The optimization process is started by applying the method described in Section 3 to the integrating process. When the specified number of iterations is reached, the optimization stops and the controller parameters are determined. Table 2 lists the obtained PI-PD controller parameters. Also, the table includes the controller parameters that were derived using various techniques from the literature.

Table 2. Controller parameters for all Examples.

| Tuning method | Controller parameters | | | |
|---|---|---|---|---|
| | $K_p$ | $K_i$ | $K_f$ | $K_d$ |
| ***Example 1*** | | | | |
| Proposed PI-PD | 2.3096 | 2.9454 | 2.9564 | 2.5511 |
| Kaya I-PD – ISTE [37] | - | 8.7408 | 9.073 | 4.3823 |
| Kaya I-PD – IST$^2$E [37] | - | 6.3714 | 7.7540 | 3.6831 |
| Chakraborty I-PD [26] | - | 0.8676 | 2.6680 | 1.1152 |
| Ali and Majhi PID [18] | 3.7550 | 1.6312 | - | 2.6323 |
| ***Example 2*** | | | | |
| Proposed PI-PD | 0.1581 | 0.0363 | 0.3974 | 0.4391 |
| Kaya PI-PD [9] | 0.0680 | 0.0340 | 0.4630 | 0.3230 |
| Padhy and Majhi PI-PD [25] | 0.0848 | 0.0451 | 0.4998 | 0.5000 |
| Tan PI-PD [6] | 0.0700 | 0.0300 | 0.4130 | 0.2000 |
| Onat PI-PD [24] | 0.1070 | 0.0393 | 0.4390 | 0.3412 |
| Raja and Ali PI-PD [4] | 0.1650 | 0.0314 | 0.3800 | 0.3800 |

The time response characteristics are shown in Table 3 and the unit step responses are illustrated in Figure 4, after applying the controller parameters given in Table 2 to the integrating process. When Figure 4 is examined, it is seen that the proposed method is quite superior to other methods, especially in terms of settling time. When the rise and peak times are compared, it is clear that satisfactory results are obtained with the proposed method. It is also obvious that the maximum overshoot value is lower than the results obtained with other methods. In order to compare the controller performances, a disturbance input with an amplitude of -0.5 is applied to the systems at t=15s, and the results are presented in Figure 4. It is observed that the proposed method eliminates the disturbance in a very short time without oscillation.

Since parameter uncertainty often exists in real systems, it will be useful to examine the performance of the designed controller under parameter uncertainty. Let's assume that there is uncertainty in the four parameters of the transfer function given in Equation 7, and let's assume this system as in Equation 8.

$$G_1(s) = \frac{e^{-[0.16,0.24]s}}{[0.08,0.12]s^3 + [1.02,1.22]s^2 + [1.1,1.3]s} \qquad (8)$$

By choosing four points for each parameter of the transfer function in Equation 8, 256 transfer functions are obtained. When PI-PD controller parameters are applied to these transfer functions as $K_p$=2.3096, $K_i$=2.9454, $K_f$=2.9564 and $K_d$=2.5511 the unit step responses of the obtained closed-loop system are obtained as in Figure 4. It can be seen from Figure 4 that the designed controller provides a robust control for the system with parameter uncertainty.

Table 3. Time response specifications for all Examples.

| Tuning method | Time specifications | | | |
|---|---|---|---|---|
| | *Rise time* | *Settling time* | *Peak time* | *O.S (%)* |
| ***Example 1*** | | | | |
| Proposed PI-PD | 0.8931 | 1.6664 | 3.7639 | 1.5234 |
| Kaya I-PD – ISTE [37] | 0.7950 | 5.4670 | 3.0035 | 11.8100 |
| Kaya I-PD – IST$^2$E [37] | 1.0125 | 3.8730 | 3.3164 | 5.9000 |
| Chakraborty I-PD [26] | 4.5106 | 9.0995 | 30 | 0 |
| Ali and Majhi PID [18] | 0.6782 | 6.4836 | 2.7598 | 28.8590 |
| ***Example 2*** | | | | |
| Proposed PI-PD | 3.1591 | 10.7062 | 14.3003 | 1.5074 |
| Kaya PI-PD [9] | 6.5245 | 18.5726 | 56.9760 | 0 |
| Padhy and Majhi PI-PD [25] | 7.4118 | 12.9006 | 20.4859 | 0.4426 |
| Tan PI-PD [6] | 4.6563 | 20.6927 | 10.7069 | 6.2233 |
| Onat PI-PD [24] | 3.8028 | 15.7837 | 8.6488 | 1.8784 |
| Raja and Ali PI-PD [4] | 3.0613 | 13.6315 | 7.5235 | 4.9563 |

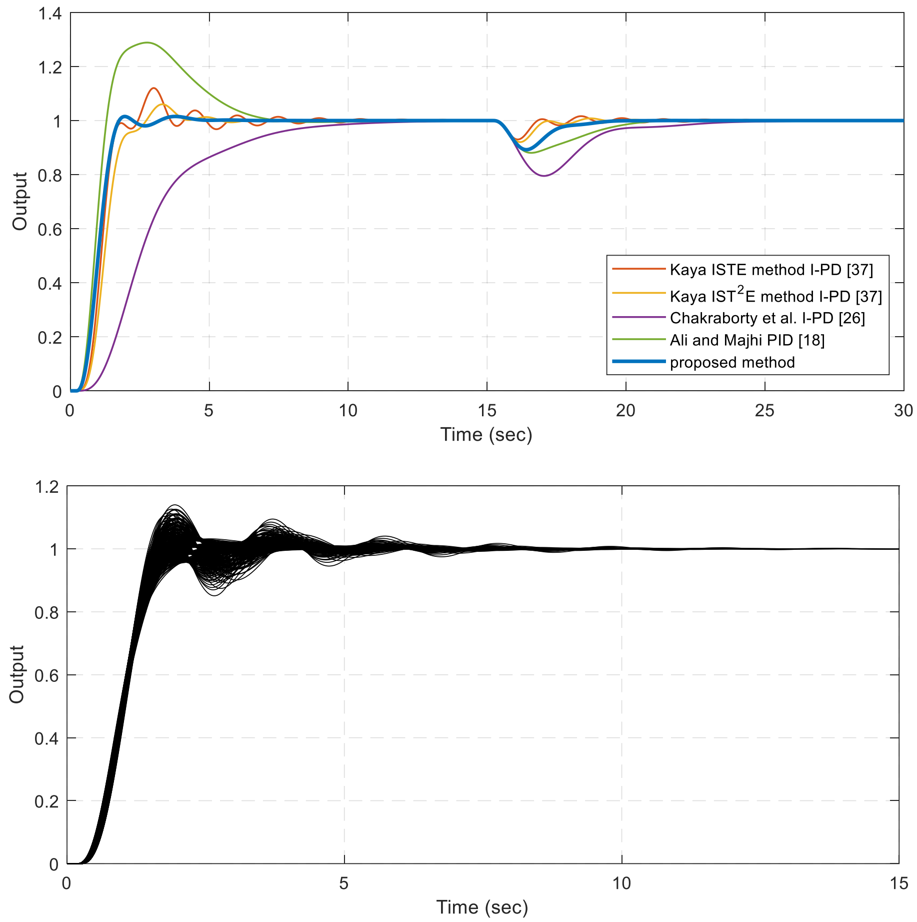



Figure 4. System output responses for Example 1 (*top*: Set-point and disturbance step responses, *bottom*: Step responses for 256 transfer functions for parameter uncertainty).

**Example 2:** Consider the transfer function of an unstable first order plus dead time system.

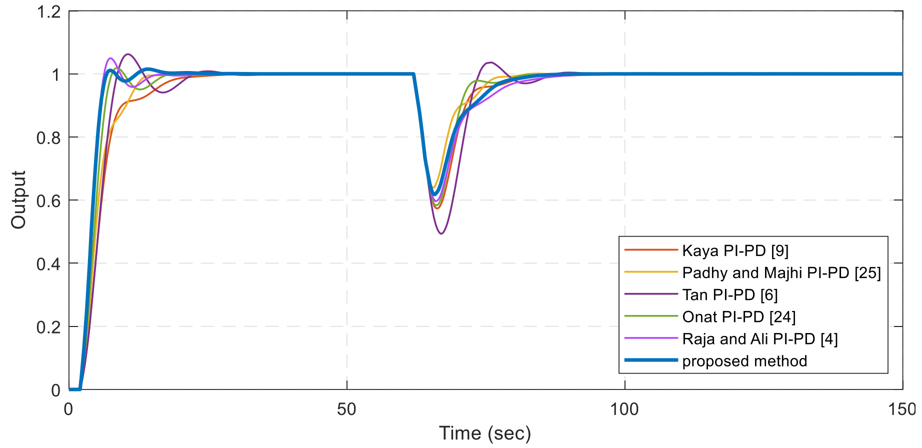
$$G_2(s) = \frac{4e^{-2s}}{(4s-1)} \tag{9}$$

The classification of a system as unstable is based on the presence of one or more poles in the right half-plane of its transfer function. An unstable system is represented by the chosen sample. The aim is to determine the controller parameters that stabilize the system and meet the design requirements set out at the outset. The rise, settling, and peak times of less than 4s, 11s, and 8s, respectively, are sufficient for good control. Desired design criteria are that the maximum overshoot should be less than 4%, and the steady-state error should be less than 0.005. The optimization process begins with the definition of the objective function and the application of the proposed method to the unstable system. When the optimization stops, the optimal PI-PD controller parameters are determined in Table 2.

The unit step responses obtained by applying the proposed method and the PI-PD controller parameters found in five different methods in the literature to the system are given in Figure 5, and the time response characteristics of these responses are given in Table 3. In addition, the performances of the systems are compared by applying -0.1 amplitude disturbance input at t=60s. It is noteworthy that the controller designed with the proposed method provides a faster settling time for the system compared to the controllers designed with other methods. It can be seen from Figure 5 that the proposed method also performs successful control in criteria such as maximum overshoot, rise time, and disturbance rejection.

In this example, as in other examples, the robustness of the system is tested, and the results are presented in Figure 5. In Equation 10, uncertainty limits are determined for four parameters, and a total of 256 transfer functions are created by choosing four values for each parameter.

$$G_2(s) = \frac{[3.8, 4.2]e^{-[1.9, 2.1]s}}{[3.8, 4.2]s - [0.9, 1.1]} \tag{10}$$



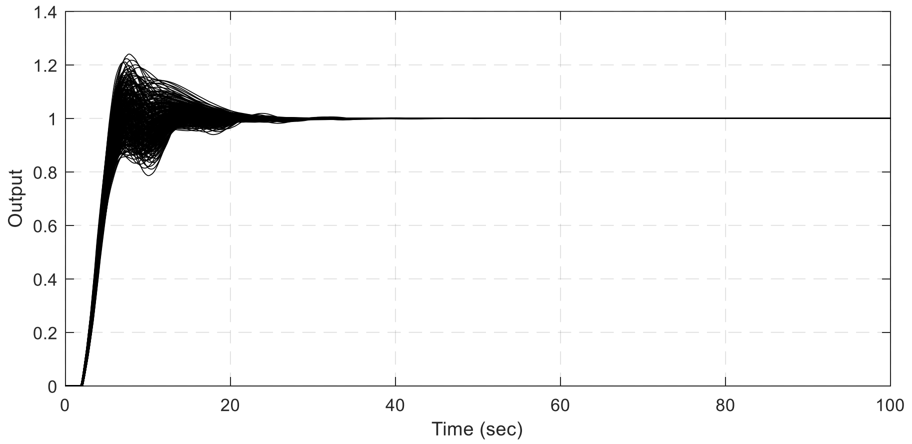




Figure 5. System output responses for Example 2 (*top*: Set point and disturbance step responses, *bottom*: Step responses for 256 transfer functions for parameter uncertainty).

## Conclusions

In this paper, an optimization method is proposed for tuning PI-PD controller parameters. The originality of the proposed method is revealed through the objective function created using the neutrosophic similarity measure. To test the performance of the proposed method, integrating and unstable plants with dead time from literature are selected. The results are presented in figures and tables in comparison with studies in the literature. Furthermore, simulations are carried out assuming that there is parameter uncertainty in the systems. The proposed method successfully controls integrating and unstable systems with time delays, including parameter uncertainty. The proposed method exhibits superiority over other methods, particularly in terms of settling time and maximum overshoot. As a result, the PI-PD controller parameters can be practically and effectively determined.

### Ethics committee approval

Ethics committee approval is not required for this study.

### Conflict of interest statement

There is no conflict of interest for this study.

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