Chapter

A Novel PID Robotic for Speed Controller Using Optimization Based Tune Technique

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Abstract

One of the most significant issue of proportional integral derivative (PID) controller is the efforts to optimize coefficient gains. Based on survey, massive tuning methods were proposed to resolve this problem but there is little pay attention to maximize minimization time response significantly. This study proposed a novel technique to maximize optimization PID gains for the DC motor controller by combining both proper tuning method with signal input signal output (SISO) optimization toolbox using optimization based tune (*OBT*) techniques, that could be utilized for the highest precision controller. The comparative study has been carried out by applying five different tuning methods to obtain a proper tuning controller, then to be combined with SISO optimization toolbox. The utilized tuning methods are Robust Auto tune (RAT), Ziegler–Nichols (Z-N), Skogestad Internal Model Control (SIMC), Chien Hroues Reswick (CHR), and Approximate M-Constrained Integral Gain Optimization (AMIGO). The performance of each tuning methods based *OBT* are analyzed and compared using MATLAB/SISO tool environment, where the efficiency has been assessed on a basis of time response characteristics (Ti) in terms of dead time (td), rise time (tr), settling time (ts), peak time (tp) and peak overshoot (Pos). The simulation results of AMIGO based proposal show a significant reduction time response characteristic to be measured in the Microsecond unit (μs). The novelty feature of the proposed is that provides superior balancing between robustness and performance. This study has been completely rewritten to account for the robotic controller development that has been taken place in the last years.

Keywords: PID controller, time response, tuning, optimization, AMIGO, DC motor

1. Introduction

A PID controller has been intensively utilized in industries for controlling feedback systems over five decades, in case of simplicity, robustness, flexibility, applicability, and satisfactory performance [1–7]. It became a standard tool and found in many engineering sectors [8, 9], playing an important role in industrial process control. Meanwhile, 60% of loops have bad performance and 25% cannot meet the performance requirements in the industry [10]. Functionally, PID is used to reduce the divergence between the set point and the process variable, which can be employed to upgrade time response and shortening the settling time of a system by tunes properly the gain parameters [11, 12].

Structurally, PID consists of three main proportional parameters, proportional gain (Kp), integral gain (Ki), derivative gain (Kd). The main function of these parameters as follows: Kp is to minimize the tr and steady-state error (Ess); Ki is to eliminate the steady-state error; Kd is to augment the system's stability, minimizing the overshoot, and enhancing the time response specification. The transfer function (TF) of PID might be realized in z-domain and s-domain [13–16]. Several criteria that influence the performance of the controller; type of algorithm, the efficiency of the tuning method, and the complexity of the design. The significant issue in the PID controller is how to tune proportional gains properly [17]. Various tuning methods had been implemented for the tuning PID controller to improve the time response specifications of the plant system by adjusting the three proportional gains. The time response specifications could be assessed in terms of tr, ts, PoS, and Ess [18]. For two decades, the process control industry has seen numerous advances as far as tuning techniques and controller design [13]. Although the PID controller has just three proportional gains, but it is quite strenuous to find out the best gains to meet desired adjustments. Enhancing the PID controller's performance might be accomplished when taking in consideration a systematic procedure of tuning proportional gains, otherwise, it is poorly tuned and raises the consumed time through process tests [3, 19]. PID tuning is extremely used to improve controller performance such as short transient, high stability makes this process harder. Practically, tuning PID gains appear to be impulsive and troublesome. The proper controller should be able to provide a system better stability by eliminating oscillation in any condition of set point [9, 20]. As shown in **Figure 1**, the tuning controller considered a vital branch of control engineers which occupied the majority of hits on the website [21]. Massive various tuning methods had been proposed to achieve satisfying control design in terms of time response specifications tr, ts, PoS, Ess. Some of these methods considered just a single of these objectives as a criterion for their tuning methods, while others considering more than one. The early tuning studies focusing on classical methods such as the Z–N oscillation method, Z- N reaction curve, Cohen Coon curve, and CHR. These traditional methods are extensively applied in cases of ease to utilize [6, 11, 22, 23]. **Figure 2** shows the comparative performance between different classical tuning methods that were used to tune the PID controller based second order system, see more details in [24]. Essentially, tuning controller methods are classified into two main sorts: open loop which indicates to tune the controller when it is in a manual state and the plant operates in an open loop and closed loop which alludes tune the controller during an automatic state in which the plant is known to process and operating in a closed loop [20]. In contrast, conventional tuning methods are still extremely utilized in an industrial

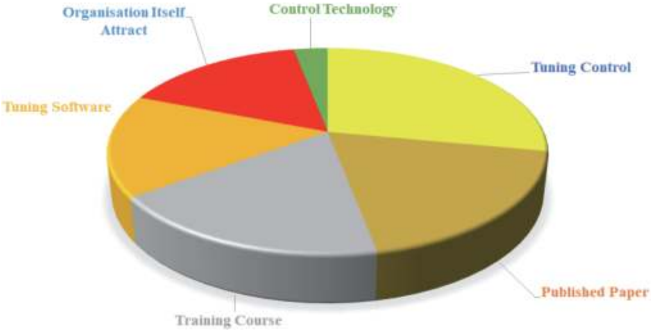

Figure 1.
A survey of PID tuning hints in website.

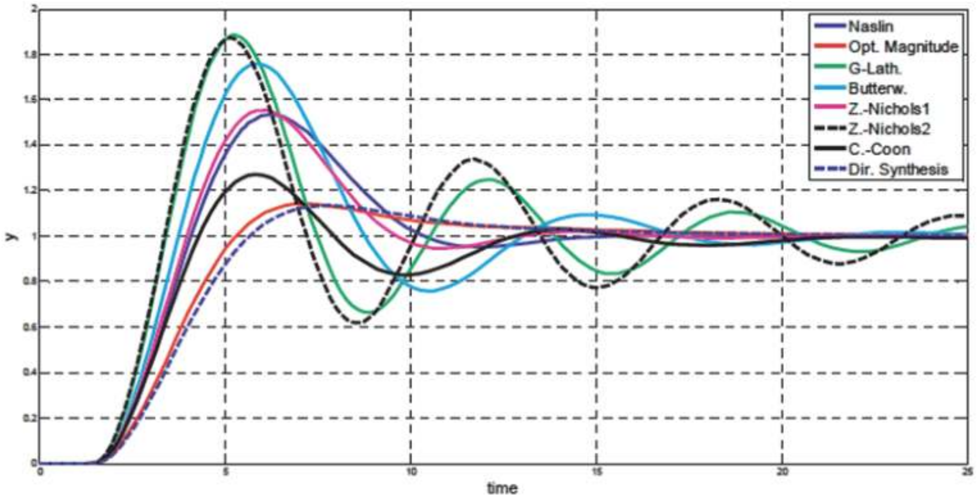

Figure 2.
Time response specifications of PID controller under different classical tuning methods [24].

controller, but they are insufficient to obtain optimal system responses besides, require additional modifications [23–26].

These disadvantages come from two reasons: 1) lacking procedure data and performance leads to poor damping; 2) the performance of the controller is affected by the parameter's variation in dynamic systems. Unstable processes are quite harsh to control compared with stable processes, and the settling time and overshoot are relatively larger for unstable systems than that of stable systems. However, development tuning methods are difficult and impractical purpose. Further, some methods are inapplicable for higher ratios of a time delay to time constant such as greater than 0.9 [13, 26]. The better tuning method depends on several criteria as follows: 1) the tuning rules should be analytical; 2) more simplicity and convenience to memorize; 3) applicable to be used in a wide range of processes [19, 27]. The majority of problems in dynamic systems are that the difficulties of describing the real plant exactly, in case of unbalancing behavior between the controller and plant system. It is necessary to extend the abilities of PID controllers to contain extra features. As some methods are better than others for various applications, each one has a negative and positive side. Several studies concentrated on the drawbacks to developing tuning methods by reducing the complexity of design and time of implementation [28–30]. The classification of the Robustness PID controller relies on what extent the robustness to minimize responses, repetition, and avoiding the growing delay time during the calculation process [19]. By contrast, optimization algorithms are effectively being implemented for adjusting gains and minimizing time response. Conventional optimization algorithms are relying on several assumptions such as differentiability, the convexity of the cost function and constraints that should be fulfilled. Optimization algorithms give better results after every iteration [31–33]. Genetic Algorithm (GA) one of the famous optimization algorithms that was invented through the 70s of the last century, which depends on parallel search techniques to adjust PID gain. However, GA suffers from the massive computational through the optimization process [4].

On the other side, a few tuning methods are extremely utilized, for example, Internal Model Control (IMC), which uses to diminish the error by expecting the output, further modifying the proportional gains to achieve the desired set-point response with accepted overshoot [34, 35]. By contrast, there are tremendous tuning methods that have been implemented to improve the precision of a controller system, but less attention has been paid in the review to combine sufficient tuning with an optimization algorithm to maximize optimization with a reduction time response. The survey shows relatively lesser studies focusing on the comparative tuning methods and limited studies for unstable systems. Additionally, there are several limitations in previous works that comes from less paid attention to take in consideration the better balancing between the overshoot and the time response parameters through tuning gains [13, 36].

In this study, we proposed a novel methodology by combined proper tuning with signal input signal output (SISO) optimization technique for adjusting PID gains to maximize minimization time response specifications of DC motor to become more proficient speed. The proposed methodology relies on a comparative study of using five different tuning methods: RAT, Z-N, CHR, Cohen, and Coon method, SIMC, and AMIGO method, applied to second order system. Afterward, proceeding a comparison between tested tuning to verify a proper tuning to be combined with optimization SISOtool. Practically, it was analyzed the time response specifications to those tested tuning methods separately and jointly with the proposed technique to estimate them in terms of td, tr, ts, and PoS.

This paper has been divided into six sections. Section 2 describes the tuning methods under test. Section 3 explained the proposed methodology. Section 4 presents simulation results based on tuning methods and proposed technique. Section 5 discusses the comparison results and PID formulation. Ultimately, the conclusion is summarized in Section 6.

2. Tuning methods under study

The problem of identification PID gains appeared when parameters of a current controller have to be tuned. In simply, if controller parameters are tuned manually with time, the controller does not achieve satisfactory performance. One important factor to be considered in designing a controller relatively with a plant is the efficiency of tuning techniques [9]. In this study, we used five different tuning methods tested with specific second order models to make a comparison and to verified the best method, prepared to combine with optimization SISO tool. In this section, we give a brief description of the selected tuning methods.

2.1 RAT tuning application

The Robust Control toolbox permits to tune control systems for robustness against parameter variation of the process, and to ensure performance across a range of operating conditions. Further, it can be used for multi model tuning to specify the best controller parameters for all plant models. There are several approaches that can be used in this application to improve tuning depends summarizes as follows: 1) Tune control system for robustness against parameter uncertainty; 2) tune fixed-structure control system against real and complex parameter uncertainty and dynamic uncertainty; 3) tune controller for a few critical values of the process parameters; 4) ensure performance across different operating conditions; 5) tune for satisfied controller over multiple system configurations [37].

2.2 Z-N tune

Z-N is a famous tuning method based on closed-loop experiments, which is widely using in process control, to achieve stability for a plant system of which the mathematical models are unknown or difficult to obtain [3, 7, 20]. It is classified into two sets, step response method and frequency response method. Z-N relies on two objectives: 1) To characterize process dynamics by two parameters, that are specified experimentally; 2) using a simple formula to figure out controller parameters from the time response characteristics. The Z-N method has had a very strong impact on the practice of the controller [1, 38]. Theoretically, Z-N relies on defining the value of Kp, Ti and Td cantered on the time response of the plant. If the model system does not have integrator and dominant merge poles, then the S-shaped curve will be shown by the unit step response curve. **Figure 3** shows the curve has two constants, time constant (T) and delay time (L) that can be obtained by drawing a tangent at the inflection point of the curve and locate the intersection of the tangent with the time axis and line c (t) = K. The compensator TF of PID controller can be obtained by setting Kp = 1.21/a, integral time Ti = 2 L and derivative time TD = 0.5 L, where a = (K.L)/T [3]. By contrast, Z-N has several drawbacks, for instance, once the controller is tuned by the Z-N method, good adjusting but not accomplished optimal responses, leads to face a lot of obstacles through implementation. Further, it suffers from time consuming, which may require many trials to obtain optimal gains, and inapplicable for unstable open loop system. Moreover, it is suitable to be used with a specific plant, but the transient response can be even worse when the system fluctuates. Additionally, due to a set point's variation or external disturbances, this leads to forces the process into an unstable operation situation. Fixing PID parameters causes leakage responses and bad performance indices. Consequently, Z-N tuning without modifications does not work well with all processes. However, these disadvantages can be resolved by using a simple modification for processes to overcome the leakage of the time delay [6, 18, 20, 39].

2.3 SIMC tune

To overcome the disadvantages over classical methods, a new merged structure with PID was proposed IMC- PID relay on pole-zero conversion for stable and unstable processes with time delay. In 2010 Shamsuzzoha and Skogestad proposed a modification to the Z-N symbolized SMIC referred as Internal Model Control that could be used to enhance the PI/PID controller for an unidentified process by utilizing closed-loop experiments. This method relies on classical ideas presented earlier by Ziegler and Nichols. The importance of this method is that there is a single tuning parameter was proposed to modify PID gains optimally and to obtain better

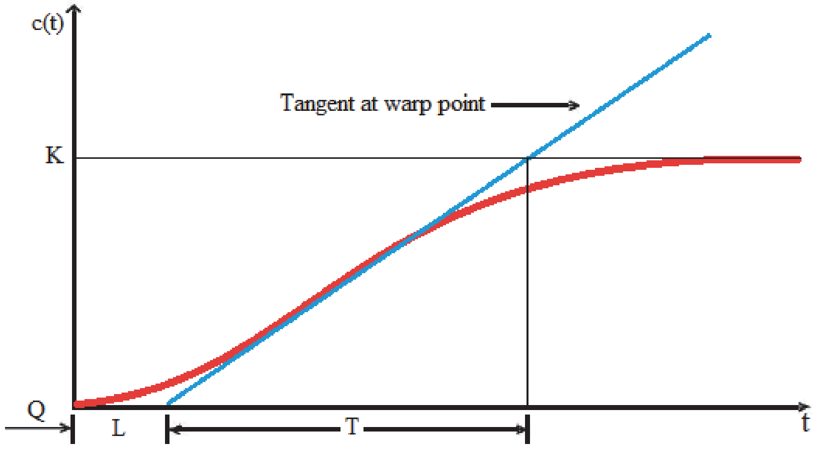

Figure 3.
Step response of plant based Z-N tune [3].

balancing between performance and robustness without needing any experimental tune, but this method still needs additional modification to get optimal gains [6, 12].

An IMC-PID controller obtains superior performance and adequate set-point tracking but displays low responses to disturbances, especially for lag-dominant including integrating processes. This approach has several advantages, such as considers model uncertainty and allows the designer to trade-off control system performance against control system robustness, to process changes and modeling errors. It is well known that the tuning parameters should be selected in a moderate way to achieve justified balancing of both robustness as well as performance. The accuracy of IMC tuning can be determined by the effective influence on the performance of the controller, which fundamentally relies on the construction of the IMC filter. Consequently, the ideal IMC filter structure must be chosen considering the performance of the resulting PID controller rather than that of the IMC controller. In this method, a lesser value for tuning parameters gives a good nominal performance, where a higher value gives robust control performance with a compromise on nominal responses. There is another drawback with traditional IMC based PID approaches is that the IMC filter is usually selected based on the performance of the resulting IMC tune not on the time response specifications of the PID controller. For this reason, it is very beneficial to convert an IMC controller to a PID controller (IMC-PID approaches) to increase the performance reduction responses. Significantly, the resulting PID controller could have poor control performance when an IMC filter structure involves an error in its conversion to the PID controller, despite being derived from the best IMC performance. The accuracy of PID based IMC tune relies on both dead time approximation error and the conversion error that relates to the filter structure and the process model. Hence, to improve PID performance, it should be taken into consideration the best roles to design the IMC filter optimally for each specific process model. As shown in **Figure 4**, the IMC structure constructed from three block: 1) Gp is referred to process; 2) Gm is referred as the process model; 3) GcI is the IMC controller. This method contributes to reduced integral time for processes, but with a large process time constant. Theoretically, this system relies on extra new parameters that can be used significantly to minimize responses by optimizing PID gains. **Figure 5** shows these parameters: Controller gain (Kc0); set point change (Δys); time from set point change to reach a first maximum peak (tp); corresponding maximum output change (Δyp); output change at first undershoot (Δyu) [13, 20, 39].

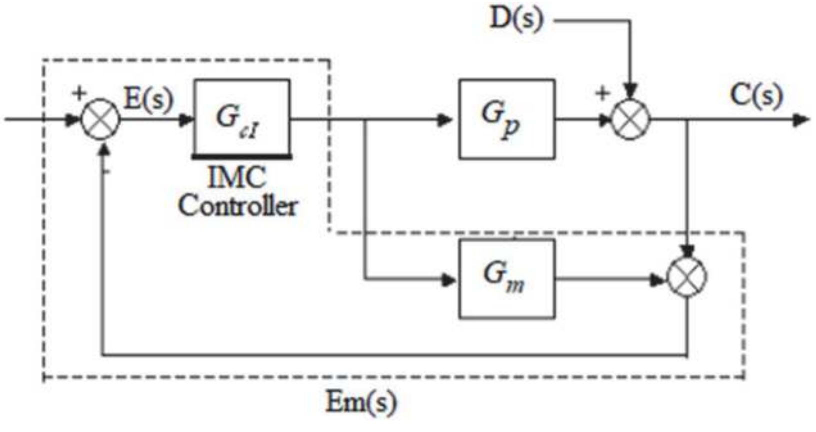

Figure 4.
IMC structure [6].

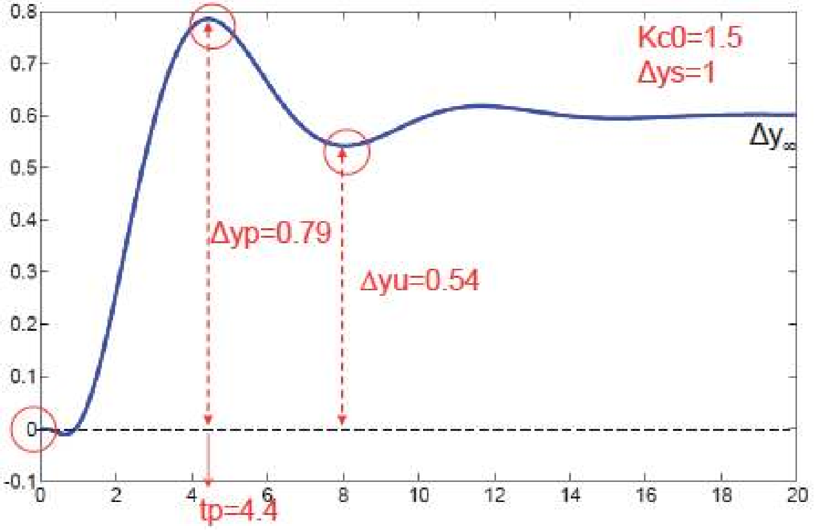

Figure 5.
Extracting parameters from IMC closed-loop set point response with PID controller [20].

2.4 CHR tune

In 1952 Hrones and Reswich proposed a modification of the open loop Z-N method to improve the time response and overshoot. They proposed to use the fastest responses with a 20 percentage overshoot as a design criterion. This method can be used for point regulation or noise rejection to control the responses to obtain better performance even at higher order system [3, 6, 40]. The set point tracking of PID controller parameters can be specified for zero percentage overshoot Kp = 0.6/a, Ti = T, TD = 0.5 L, where the parameters value in 20 percentage of the overshoot are Kp = 0.95/a, Ti = 1.4 T, TD = 0.47 L. Tuning rules based on 20 percentage overshoot design criteria are quite like the Z-N method. On the other side, when zero percentage overshoot criteria are utilized, the integral time is larger and the gain and the derivative time are smaller, that's mean a proportional action and an integral action, as well as a derivative action, are smaller. By contrast, both of Z-N and CHR method use the time constant T delay time L and gain k of the plant explicitly [1, 6, 8].

2.5 AMIGO tune

The procedure of the AMIGO tune is similar to that of the Z-N tune method. This method gives a controller more capability to reduce load disturbances effectively, besides maintaining good robustness. Theoretically, the time constant of this method can be obtained by Aström's equations. Essentially, the design procedures performed on loop shaping provides satisfaction integral gain subject to a robustness constraint. The robustness could be verified in terms of the maximum value of the sensitivity function. Therefore, the AMIGO tune can be represented as a minimization of the integrated error at step load disturbances subject to constraints on the maximum sensitivity [3, 38, 41].

3. Methodology

This section describes the system under study and proposed technique of how to use both tuning PID with optimization SISO tool to minimize Ti and Pos significantly. The novelty of the proposed technique is to maximize the minimization time response of the controller as will be explained in the following sections.

3.1 Mathematical model of speed DC motor

To design a PID controller precisely, it is essential to evaluate the mathematical model of the selected DC motor, then applying the proposed methodology. The mathematical model of the DC motor was derived based on Eq. (6). In this model we assume that the back emf (Ke) and motor torque (Kt) are equal, therefore:

$$Kt = Ke = K \tag{1}$$

$$Ki = J.\ddot{\theta} + \mathrm{b}.\dot{\theta} \tag{2}$$

$$V - K\dot{\theta} = L.\frac{di}{dt} + Ri \tag{3}$$

By applying the Laplace transform to get s-domain equations:

$$s(Js + b)(s) = KI(s) \tag{4}$$

$$(Ls + R)Is = V(s) - Ks(s) \tag{5}$$

Where, L is the electric inductance, R is the resistance of the coil, b is motor viscous friction constant, $\theta$is the speed of the shaft, Kt motor torque constant, Ke electromotive force constant, and J is the moment of inertia of the rotor.

By eliminating I (s), it can be derived the mathematical model of speed DC-Motor, and substituted the following DC motor parameters in Eq. (6). The speed mathematical model of the selected DC motor can be derived as given in Eq. (7):

L = 0.5H, R = 1 Ω, b = 0.1 N.m. s, Kt = 0. 01 N.m/Amp, Ke = 0.01 V.sec/(rad), J = 0.01 kg. m^2.

$$P(s) = \frac{\dot{\theta}}{V(s)} = \frac{K}{(Js + b)(Ls + R) + K^2} \frac{[rad/\sec]}{V} \tag{6}$$

$$P(s) = \frac{0.01}{0.005\,S^2 + 0.06\,S + 0.1001} \tag{7}$$

3.2 Proposed technique

It was suggested a new technique to optimize the PID gains by following two stages. Initially, we utilized five different traditional tuning methods RAT, Z-N, SIMC, CHR, and AMIGO to tune the PID controller lonely, and to produce compensator TF prepared to be imported to the next stage. Secondly, to improve the reduction Ti and Pos for the chosen model by using *OBT* technique, where this methodology needs a benchmark comparison to nominate the best tuning method to be joined with the SISO toolbox application. In view of the two ideas suitability of optimization and time response parameters, we perform a comparison between tuning understudy independently and jointly to prove the validation of the proposed technique, using the SISO optimization based tune ($\boldsymbol{SISO_{OBT}}$). All tuning methods under study are mimicked by giving a unit step change in set point.

The $\boldsymbol{SISO_{OBT}}$ technique provides two significant aspects. Firstly, how changes in the TF's poles and zeros alter the root locus and bode plots in live response, besides tracking the changes in gains that can influence to system's step response. Secondly, specifying the design requirements will create visual limitations on the graphs to help the user set and find appropriate gains. The time response of the DC motor model was simulated using MATLAB code. The Ti results based proposed technique have been contrasted with each other existing tuning methods. This is done by chosen" Design Requirements" on the SISO tool root locus plot set and define its limits on the characteristic of the time response. It was investigated the criteria which affect the controller performance in terms of td, tr, ts, steady state time (SST), tp, Overshoot PoS, and number of Iterations. **Figure 6** presents the proposed technique to optimize PID gains which rely on several steps as follows: 1) Import the mathematical model into estimation tool; 2) putting compensator gain to 1 and selecting r to y for negative feedback controller using step response for analysis plot; 3) measuring the time response specifications by LTI viewer; 4) adding the PID controller to a system and applied the tested tune based step response to extract proportional gains, then updating the compensators gain and TF. This is the first stage of adjusting PID gains; 5) preparing to optimization stage, on LTI viewer specifying the design requirements as the following; tr 1e-8 for 90%, ts 2e-8, *PoS* 2; 6) readjusting the location of compensator Zeros for fine modification proportional gains, using optimization SISO closed loop r to y; 7) from LTI viewer import TI and Pos, it can be seen that there is a magnificent reduction time response contrasted with the first level tuning; 8) import the TF of compensator with optimization proportional gains; 9) using switching mod algorithm to select one by one different tuning methods RAT, Z-N, SIMC, CHR, AMIGO and repeat those steps 1–8 for each one. The last step provides comparison results between tuning under study based proposed methodology to select a suitable tune that could be chosen to finalize the design based proposed methodology.

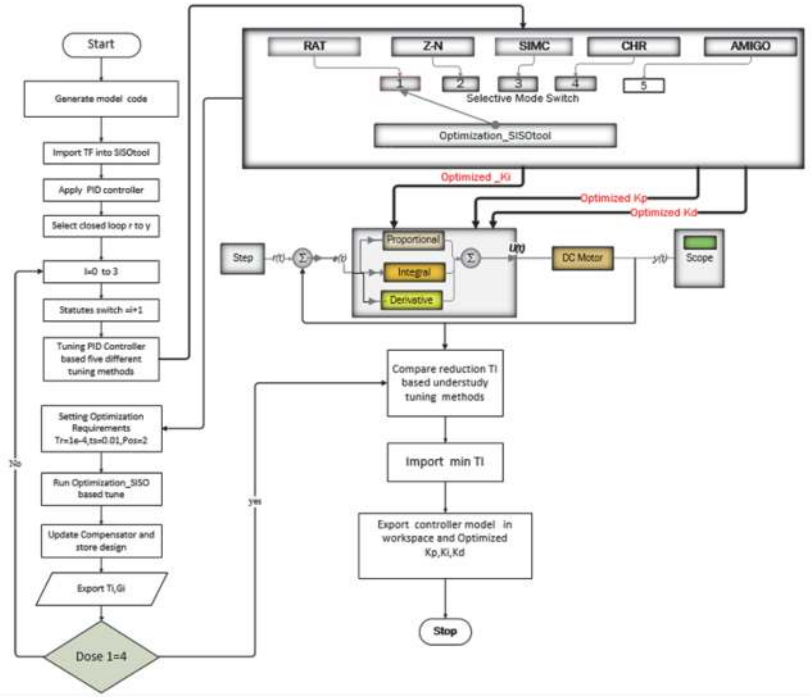

Figure 6.
The PID controller based proposed technique.

4. Results and analysis

This section illustrates the simulation results in terms of time response specifications, proportional gains and poles zeros locations. The performance of the proposed method was tested with the TF of the plant model as given in the aforementioned Eq. (7). **Figure 7** shows the transient response of an uncontrolled system under study. It can be seen that the system is very slow response measured in second (s) unit, where the time response characteristics are: td = 44 ms, tr = 0.627 s, ts = 1.13 sec, tp1.85 s, SSt 1.8 s, and peak amplitude 0.0476. The proposal relies on two levels of tuning. Firstly, we used RAT, Z-N, SIMC, CHR, and AMIGO tuning methods to tune the PID controller separately and to obtain a comparison between them in terms of time response characteristics. Further to generate a compensator TF prepared to be used as a modified system. The obtained gains are used as a first tuning level. Secondly, combine tuning methods with optimization SISO toolbox application using *OBT* technique to optimize PID gains generated by the first tuning level. Where the obtained results are used as a second tuning level.

Figures 8–12 presents the Ti characteristics of the system under separately tuning and based *OBT* for the tested tuning methods. **Figure 8(a)** shows the time response of the system using the RAT lonely. The obtained results are: PoS = 6.24%, td = 0.102 s, tr = 0.267 s, ts = 0.935 s, constant time = 1.5 s, where tuning gain values are: Kp = 319, Ki = 1/Ti = 1.79e+03 and Kd = 4.22. **Figure 8(b)** shows the time response by RAT based *OBT* $(\boldsymbol{RAT_{OBT}})$. It is obviously seen that there is significantly improved time response and overshoot as follow: td = 0.0943 ms, tr = 0.31 m s,

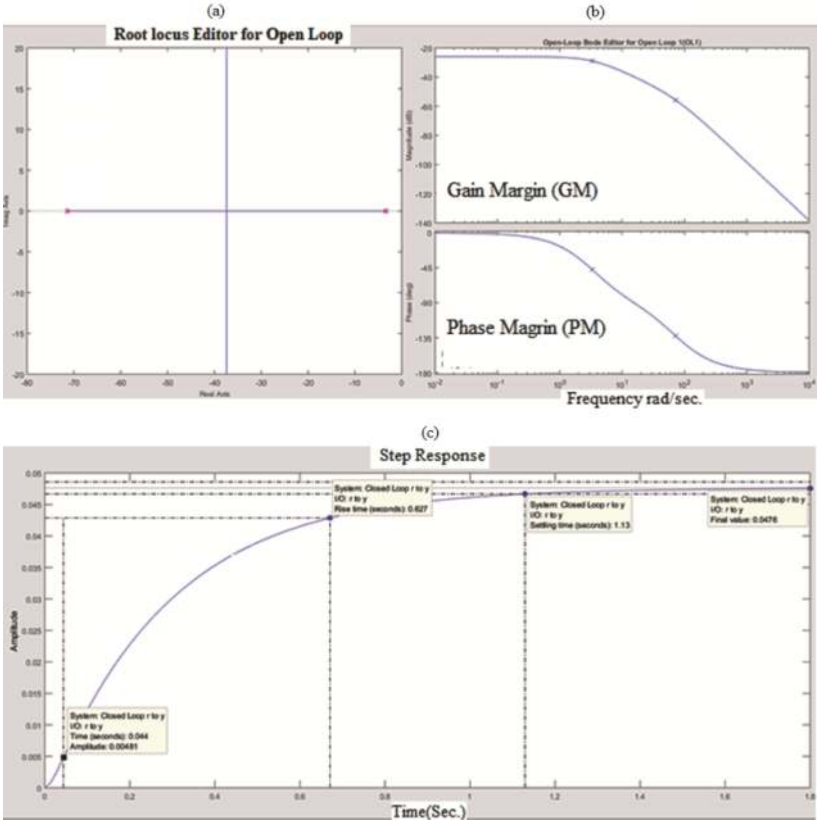

Figure 7.
Tested uncontrolled system, (a) poles zeros location, (b) gain and phase margin, (c) time response characteristics.

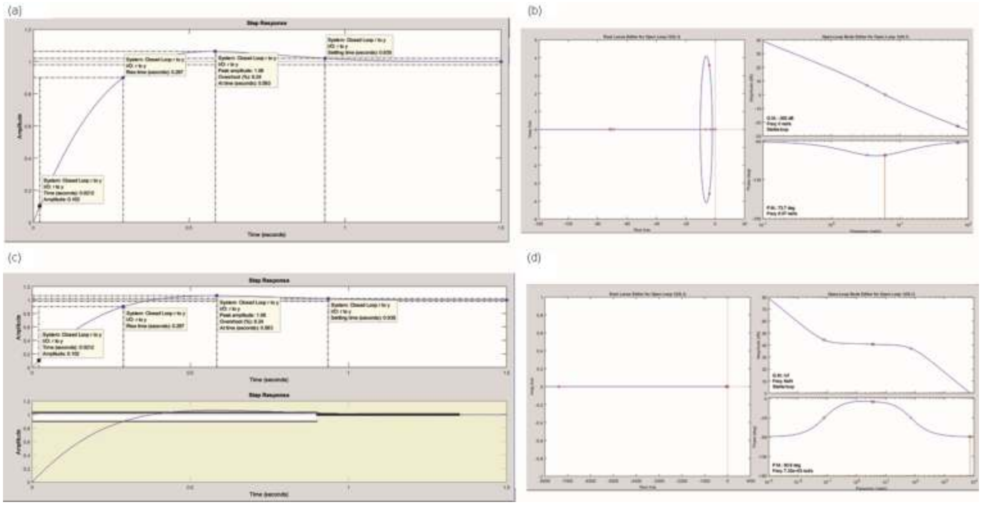

Figure 8.
Step response and poles zeros location of controller system based RAT separately tune and $\mathrm{RAT}_{\mathrm{OBT}}$, *(a) step response based RAT separately tune, (b) poles zeros location and gain/phase margin based separately tune, (c) step response based* $\mathrm{RAT}_{\mathrm{OBT}}$, *(d) poles zeros location and gain/phase margin based* $\mathrm{RAT}_{\mathrm{OBT}}$.

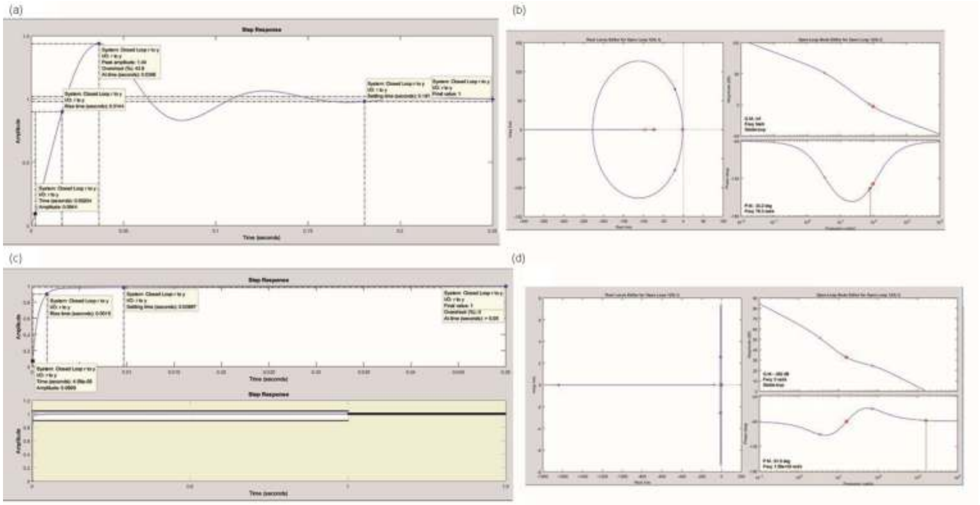

Figure 9.
Step response and poles zeros location based Z-N tune and $\mathrm{Z\_N}_{\mathrm{OBT}}$, *(a) step response based Z-N separately tine, (b) poles zeros location and gain /phase margin based Z-N separately tune, (c) step response based* $\mathrm{Z\_N}_{\mathrm{OBT}}$, *(d) poles zeros location and gain /phase margin based* $\mathrm{Z\_N}_{\mathrm{OBT}}$.

ts =0.617 ms, constant time = 1.4 ms, PoS = 0%, where the tuning gains values are; Kp = 4.6888, Ki = 1/Ti = 181 and Kd = 615. **Figure 8(c,d)** show the root locus of controller based RAT lonely and $\boldsymbol{RAT_{OBT}}$ respectively,it is obviously to seen that the modification of zeros location based $\boldsymbol{RAT_{OBT}}$ produces high adjusting location compared with other tuning based OBT. **Figure 9(a)** shows the time response of the model based Z-N tuning lonely. The obtained time response results are:
PoS = 43.8%, td = 0.0944 s, tr = 0.0144 s, ts = 0.181 s, constant time = 0.25 s, where tuning gain values are: Kp = 13.9269, Ki = 1/Ti = 10.656875 and Kd = 36.2. **Figure 9(b)** shows the time response produced by Z-N based OBT ($\boldsymbol{Z\_N_{OBT}}$). It is obviously seen that there is significantly improved time response and overshoot as follow: td = 2.2 Micro s, tr = 0.0015 s, ts = 0.00967 s, T = 0.05 s, PoS = 0%., where the tuning gains values are: Kp = 10.67551, Ki = 1/Ti = 10.6568757 and Kd = 2.5938410. **Figure 9(c,d)** illustrate the root locus of the controller based Z-N lonely and $\boldsymbol{Z\_N_{OBT}}$ respectively.

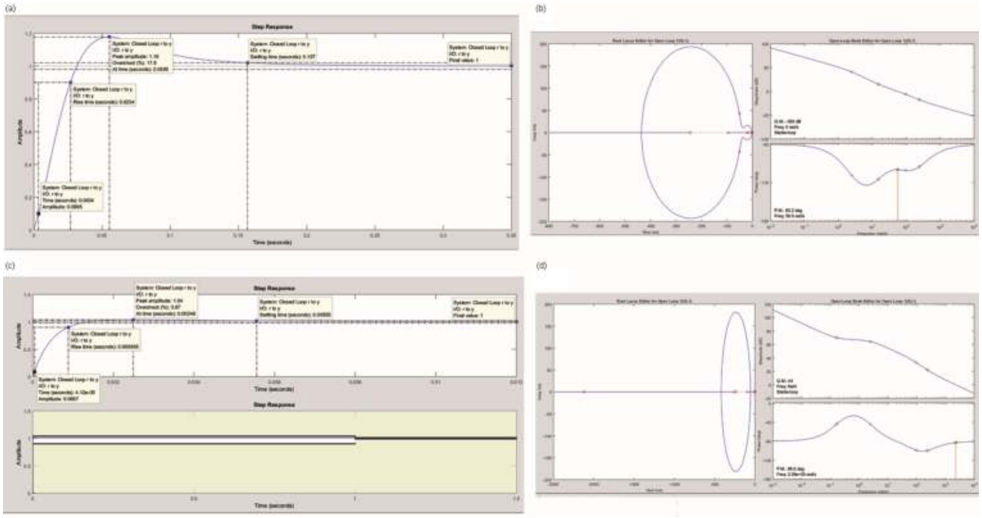

Figure 10.
Step response and poles zeros location based SIMC tune and SIMC$_{OBT}$*, (a) step response based SIMC separately tine, (b) poles zeros location and gain/phase margin based SIMC separately tune, (c) step response based* SIMC$_{OBT}$*, (d) poles zeros location and gain/phase margin based* SIMC$_{OBT}$*.*

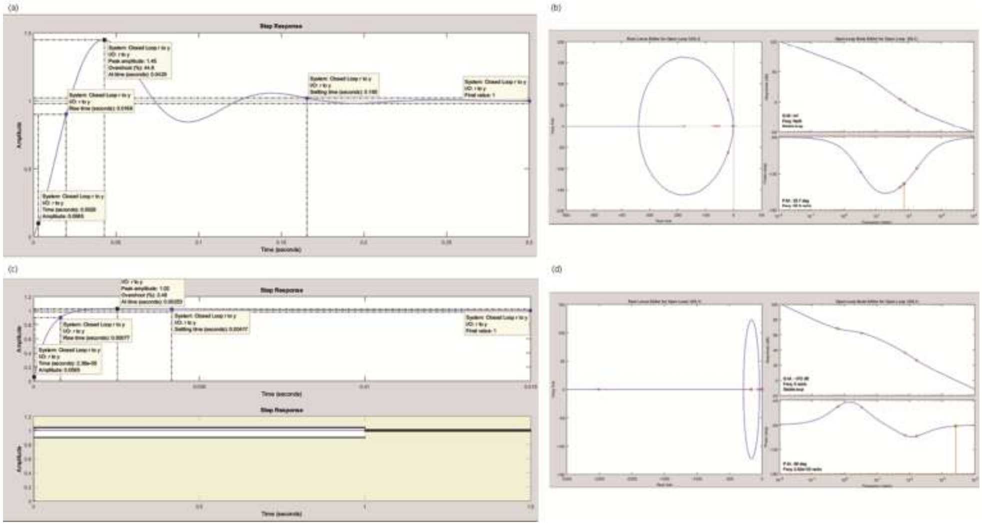

Figure 11.
Step response and poles zeros location based CHR tune and CHR$_{OBT}$*, (a) step response based CHR separately tine, (b) poles zeros location and gain/phase margin based CHR separately tune, (c) step response based* CHR$_{OBT}$*, (d) poles zeros location and gain/phase margin based* CHR$_{OBT}$ *.*

It is obviously seen that the modification of zeros location based $\boldsymbol{Z\_N_{OBT}}$ produces high adjusting location compared with tuning lonely.

Afterward, we will investigate the tuning gains based SIMC separately and jointly with optimization SISO application, and what happens to time response characteristics with overshoot. **Figure 10(a)** presents the time response of the model based SIMC tuning method. The obtained results are: td = 0.0034 s, tr = 0.0234 s, ts = 0.157 s, constant time = 0.35 s, Pos = 17.8%, where tuning gain values are; Kp = 5.29e+0.3, Ki = 1/Ti = 7.55e+0.4 and Kd = 20.6. **Figure 10(b)** shows the time response by SIMC based proposed method ($\boldsymbol{SIMC_{OBT}}$). It is obviously seen that there is significantly improved time response and overshoot as follow: td = 4.12e-05 s, tr = 0.835 ms, ts = 5.5 m s, constant time = 0.012 s, PoS = 3.87, where the tuning gains values are: Kp = 4.54e+05, Ki = 1/Ti = 7.55e+04 and Kd = 1.92e+03.

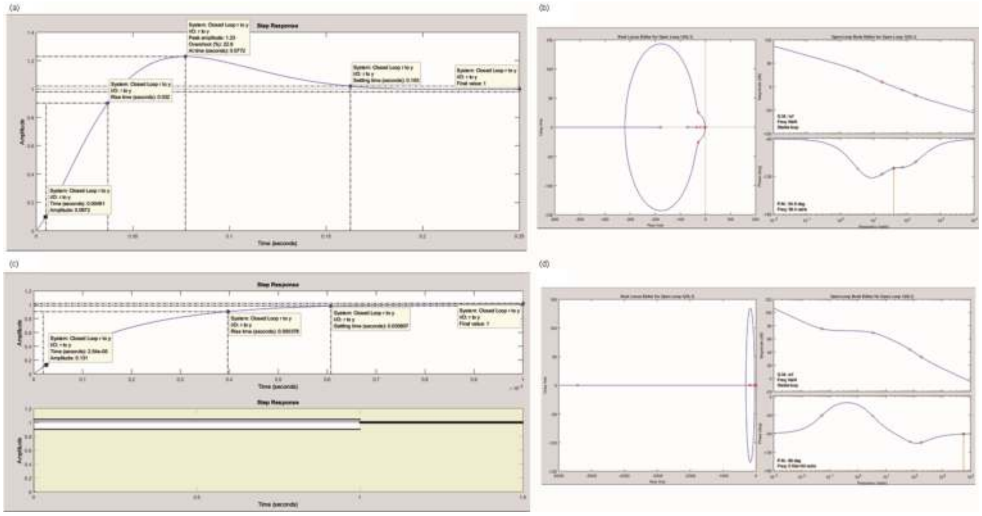

Figure 12.
Step response and poles zeros location based AMIGO tune and AMIGO$_{\text{OBT}}$*, (a) step response based AMIGO separately tine, (b) poles zeros location and gain/phase margin based AMIGO separately tune, (c) step response based* AMIGO$_{\text{OBT}}$*, (d) poles zeros location and gain/phase margin based* AMIGO$_{\text{OBT}}$ *.*

Figure 10(c,d) illustrate the root locus of the controller based SIMC lonely and **$SIMC_{OBT}$** respectively, it is obviously to seen that the modification of zeros location by **$SIMC_{OBT}$** produces high adjusting location compared with other tuning based OBT. **Figure 11(a)** shows the time response of the system using CHR tuning method lonely. The obtained results are: td = 0.0029 s, tr = 0.0168 s, ts = 0.165 s, constant time = 0.3 s, PoS = 44.8%. Tuned gain values are: Kp = 553, Ki = 1/Ti = 2.24e+04 and Kd = 2.41. **Figure 11(b)** illustrates the time response produced by CHR based OBT (**CHR_{OBT}**) as follow: PoS = 2.48, td = 2.36e-05 s, tr = 0. 77 ms, ts = 4.1 m s, constant time = 0.015 s, where the tuning gains values are: Kp = 3.62e+04, Ki = 1/Ti = 2.24e+04 and Kd = 219. **Figure 11(c,d)** illustrate the root locus of controller based CHR lonely and **CHR_{OBT}** respectively,it is obviously to seen that the modification of zeros location by **CHR_{OBT}** produces high adjusting location compared with tuning lonely.

Figure 12(a) shows the time response of the system using AMIGO tuning method. The obtained simulation results are: PoS = 22.9%, td = 0.00491 s, tr = 0.032 s, ts = 0.1635s, constant time = 0.25 s, where, tuning gain values are: Kp = 2.66e+03, Ki = 1/Ti = 4.24e+04 and Kd = 13.6. **Figure 12(b)** shows the time response by AMIGO based proposed method (**$AMIGO_{OBT}$**). It is obviously seen, that there is significantly improved in time response and overshoot compared with others as the following results: Pos = 0%, td = 2.54e-05 s, tr = 0. 378 ms, ts = 0.607 m s, constant time = 1 ms, where the tuning gains values are: Kp = 8.18e+03, Ki = 1/Ti = 4.24e+04 and Kd = 4.64e+03. **Figure 12(c,d)** present the root locus of the controller based AMIGO lonely and **$AMIGO_{OBT}$**. It is clearly seen that the modification of zeros location based **$AMIGO_{OBT}$** produces a high adjusting location compared with compared with tuning lonely.

Table 1 shows the TF and proportional gains of the compensator based OBT for different tuning methods. **Figure 13** shows the modification location poles (P) zeros (Z) and adjusting compensator gains, to presents the effectiveness of using **$AMIGO_{OBT}$** over another tuning understudy. **Figure 13(a)** presents the values of P and Z for optimization under **RAT_{OBT}** as follows: 0, Z1 = −0.0785897621, Z2 = -3.7453341264 respectively, and the gain (G) = 614.6118. **Figure 13(b)** shows the values of P and Z produces by **Z_N_{OBT}** as follows: P = 0,

	Method	TF of Compensator	Gain	Peak Amplitude
Classical Tuning	RAT	$\frac{4.2238(s+69.52)(s+6.092)}{s}$	4.22	1
	Z-N	$\frac{36.173(s+96.5)^2}{s}$	36.30	1
	SIMC	$\frac{20.561(s+242.3)(s+15.15)}{s}$	20.56	1
	CHR	$\frac{2.4055(s+177.2)(s+52.58)}{s}$	2.4	1
	AMIGO	$\frac{13.632(s+177.5)(s+17.52)}{s}$	13.63	1
Proposed Technique	$\boldsymbol{RAT_{OBT}}$	$\frac{614.61(s+0.07859)(s+3.745)}{s}$	614.61	0.999
	$\boldsymbol{Z\_N_{OBT}}$	$\frac{1340.3(s+15.85)^2}{s}$	1340.25	1
	$\boldsymbol{SIMC_{OBT}}$	$\frac{1915.4(s+236.9)(s+0.1663)}{s}$	1915.36	1
	$\boldsymbol{CHR_{OBT}}$	$\frac{219.34(s+164.4)(s+0.6216)}{s}$	219.34	1
	$\boldsymbol{AMIGO_{OBT}}$	$\frac{4644.6(s+176.1)(s+0.05183)}{s}$	4644.6	1

Table 1.
Comparison modeling compensator between tuning methods under study and proposed technique.

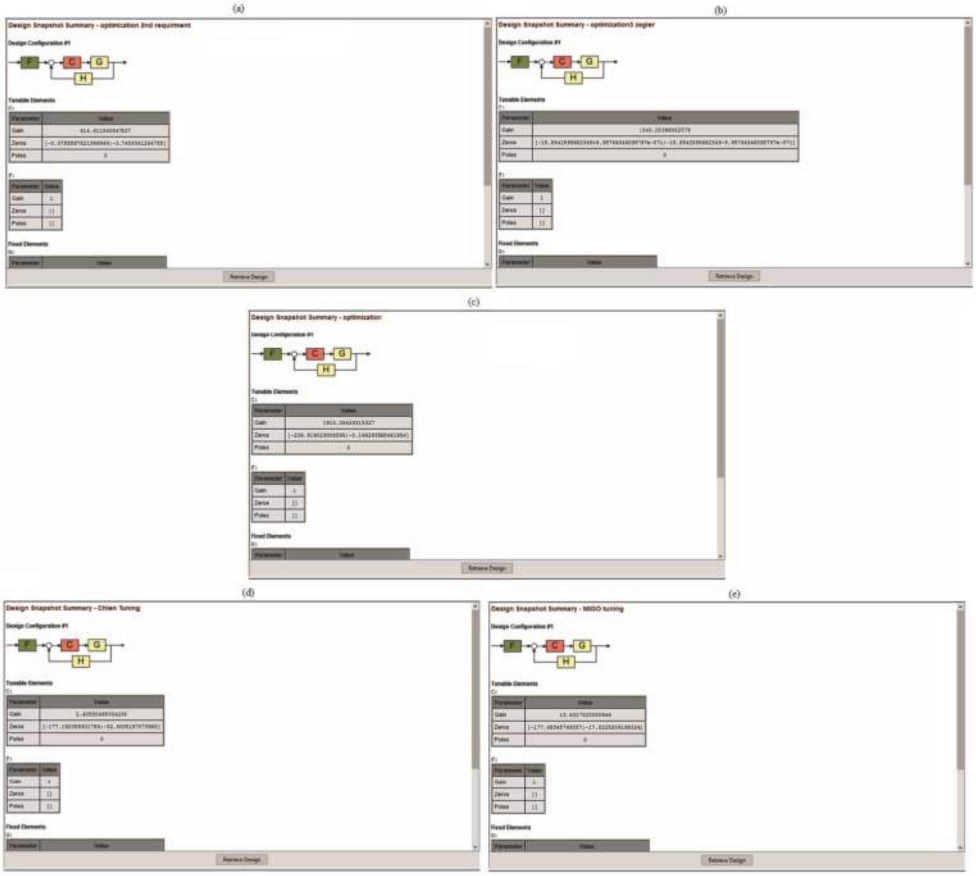

Figure 13.
Optimization results under various tuning methods in term of P, Z, Gains. (a) optimization under $\mathrm{RAT_{OBT}}$*, (b) optimization under* $\mathrm{Z\_N_{OBT}}$*, (c) optimization under* $\mathrm{SIMC_{OBT}}$*, (d) optimization under* $\mathrm{CHR_{OBT}}$*, (e) optimization under* $\mathrm{AMIGO_{OBT}}$ *.*

Z1 = −15.854289 + 8.9576434e-07i, Z2 = -15.854289–8.9576434e-07i, and G = 1340.2539. **Figure 13(c)** shows the values of P and Z on optimization under $\boldsymbol{SIMC_{OBT}}$ as follows: 0, Z1 = −236.91902, Z2 = -0.1662935 respectively, and

G = 1915.3642. **Figure 13(d)** shows the values of P and Z for optimization under $\boldsymbol{CHR_{OBT}}$ as follows: 0, Z1 = -177.192359, Z2 = -52.580519, and G = 2.405504. **Figure 13(e)** shows the values of P and Z for optimization under $\boldsymbol{AMIGO_{OBT}}$ As follows: P = 0, Z1 = -176.1048, Z2 = - 0.0518305, and G = 4644.6092.

5. Discussion

This section discussed the comparison results between tested tuning methods separately and jointly with proposed methods in terms of time domain specifications as tabulated in **Table 2**, where the evaluation benchmark is based on analyzing

	Method	**td(s)**	**tr(s)**	**ts(s)**	**tp(s)**	**SSt(s)**	**Pos %**	**ζ**	**Iter. No**
Classical Tuning	RAT	0.102	0.267	0.935	1.06	1.5	6.24	0.662	
	Z-N	0.094	0.0144	0.181	1.44	0.25	43.8	0.254	
	S IMC	0.0034	0.0234	0.157	1.18	0.35	17.8	0.481	
	CHR	0.0029	0.0168	0.165	1.45	0.3	44.8	0.247	
	AMIGO	0.00491	0.032	0.163	1.23	0.25	22.9	0.4247	
Proposed Technique	$\boldsymbol{RAT_{OBT}}$	0.000094	0.000382	0.000617	0.999	1.4 ms	Zero	Zero	9
	$\boldsymbol{Z\_N_{OBT}}$	0.00022	0.0015	0.00967	1	0.05	Zero	Zero	2
	$\boldsymbol{SIMC_{OBT}}$	0.0000412	0.000835	0.00555	1.04	0.012	3.87	0.7192	5
	$\boldsymbol{CHR_{OBT}}$	0.00002536	0.00077	0.0041	1.02	0.015	2.48	0.76202	3
	$\boldsymbol{AMIGO_{OBT}}$	0.000025	0.000378	0.000607	1 msec	1 msec.	Zero	Zero	5

Table 2.
Comparison of time response specifications between tuning methods under study and proposed technique.

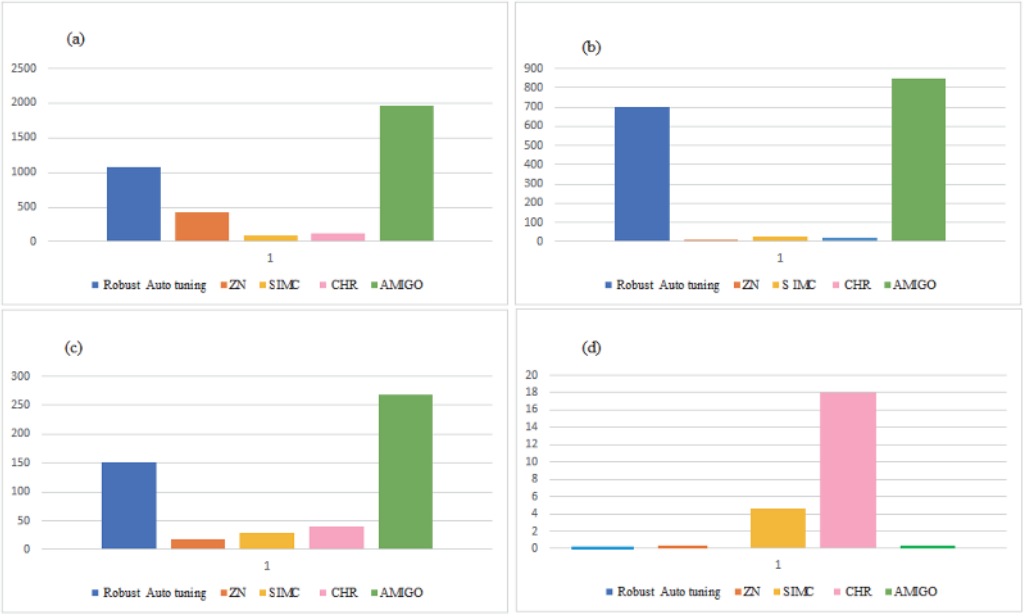

Figure 14.
Comparative improvement time response specifications between tuning methods based OBT *with respect to tuning lonely, (a)improvement td ratio, (b) improvement tr ratio, (c) improvement ts ratio, (d) improvement overshoot ratio.*

Ti and Pos. For the first level tuning, the tuning based Z-N shows that the overshoot is the largest value by 43% between other tuning methods. For the second level optimization, the time response produced by the proposed technique is quite less than by using tuning lonely. Hence, combining both best tuning methods with optimization obtained maximum minimization Ti to the considered system.

Figure 14 presents the comparative improvement time response between tuning methods based proposed technique with respect to tuning lonely, to demonstrates the effectiveness of the proposed technique. The results based $\boldsymbol{RAT_{OBT}}$ show that the improving time response ratio in terms of td, tr, ts duplicated by 1081, 699, 151 times respectively compared with RAT tuning lonely. Where, $\boldsymbol{Z\_N_{OBT}}$ raised by 429, 9.6, 18.7 times respectively. In $\boldsymbol{SIMC_{OBT}}$ boosted by 82.5, 28, 28.2 times respectively, where in $\boldsymbol{CHR_{OBT}}$ increased by 114.3, 21.8, 40.2 times respectively and in $\boldsymbol{AMIGO_{OBT}}$ increased by 1964, 846, 268.5 times respectively. According to the results, it can be observed that $\boldsymbol{AMIGO_{OBT}}$ obtains highest reduction with quit shortest responses td 25 μs, tr 378 μs, ts 607 μs, tp 1 ms, providing better optimization gains Kp 2660, Ki 42400, Kd 13.6. Hence, the time response parameters obtained by the novel proposed technique much smaller and quite acceptable than those using just tuning. It is observed that the eliminating overshoot was achieved in $\boldsymbol{RAT_{OBT}}$, $\boldsymbol{Z\_N_{OBT}}$ and $\boldsymbol{AMIGO_{OBT}}$, where it is quite small in $\boldsymbol{SIMC_{OBT}}$ and $\boldsymbol{CHR_{OBT}}$.

Figure 15 illustrates the comparative time response improvement ratio between $\boldsymbol{AMIGO_{OBT}}$ and other tuning methods based *OBT*. The time response results show that the $\boldsymbol{AMIGO_{OBT}}$ obtains superior performance over $\boldsymbol{Z\_N_{OBT}}$, $\boldsymbol{SIMC_{OBT}}$, $\boldsymbol{CHR_{OBT}}$, and produces a higher reduction time response to be measured in Microsecond unit, which gives the capability to overcome the majority of previous works further. This is typically within the required criteria for robotic applications. The final design with step response based $\boldsymbol{AMIGO_{OBT}}$ was simulated based Matlab/Simulink. **Table 3** refers to parameters of the system in terms of P and Z location and proportional gains in both separately tuning and jointly tuning based proposed method. Accordingly, the compensator TF produced by different methods is compared based on the steady state response and system characteristics. The comparison of modification Z location and adjusting compensator gains was presented to show the effectiveness of using AMIGO tune based proposed methodology over

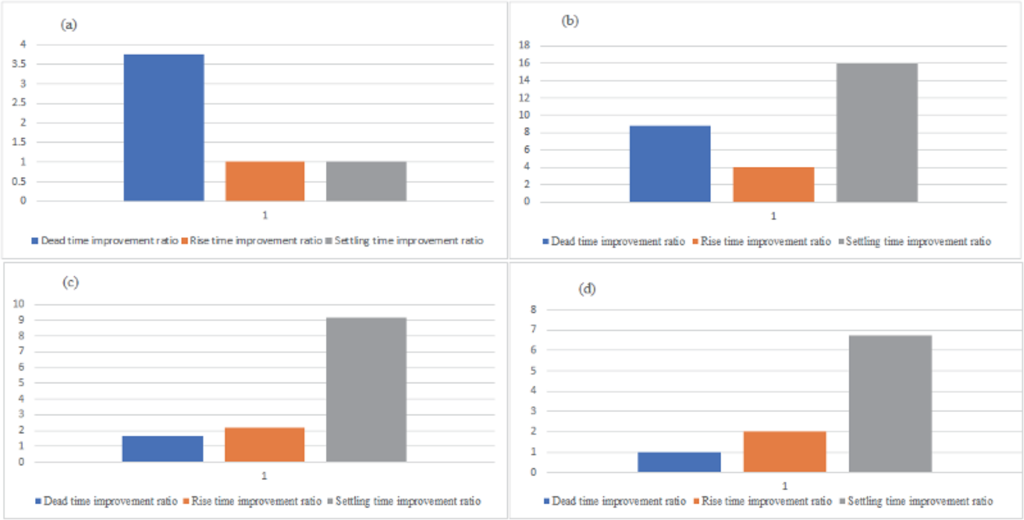

Figure 15.
Comparative time response improvement ratio between $\mathrm{AMIGO_{OBT}}$ *and other tuning methods based* OBT, *(a) improvement ratio comparing with* $\mathrm{RAT_{OBT}}$, *(b) improvement ratio comparing with* $\mathrm{Z\_N_{OBT}}$, *(c) improvement ts ratio comparing with* $\mathrm{SIMC_{OBT}}$, *(d) improvement ratio comparing with* $\mathrm{CHR_{OBT}}$.

	Method	No of Z	No of P	Z location	P location	Kp	Ki	Kd
Classical Tuning	RAT	2 real	1 real	(−69.6), (−6.1)	0	319	1790	4.22
	Z-N	2 real	1	(−96.8), (−96.8)	0	13.92693	10.656875	36.2
	S IMC	2 real	1	(−242.3), (−15.15)	0	5290	75500	20.6
	CHR	2real	1	(−177), (−52.6)	0	553	22400	2.41
	AMIGO	2 real	1	(−177.5), (−17.52)	0	2660	42400	13.6
Proposed Technique Technique	**RAT_{OBT}**	2 real	1 real	(−0.07859), (−3.745)	0	4.6888	181	615
	Z_N_{OBT}	2 complex	1 real	(−15.85 + 8.95e-07i), (−15.854–8.95e-07i)	0	10.67551	10.6568757	2.5938410
	$SIMC_{OBT}$	2real	1	(−236.9), (−0.1663)	0	454000	75500	1920
	CHR_{OBT}	2 real	1	(−177.19), (−52.58)	0	36200	22400	219
	$AMIGO_{OBT}$	2 real	1	(−176.1), (−0.05183)	0	8180	42400	4640

Table 3.
Comparison proportional gains and poles zeros location between tuning methods under study and proposed technique.

another tuning understudy. Accordingly, the compensator TF produced by different methods is compared based on the steady state response and system characteristics.

The damping ratio(ζ) can be specified by solving the Eq. (8). It can be seen that both SIMC and CHR based proposed produced highest damping ratio 0.71920, 0.76202 respectively compared with other cases, where it eliminated in $\boldsymbol{RAT_{OBT}}$ and $\boldsymbol{Z - N_{OBT}}$, $\boldsymbol{AMIGO_{OBT}}$.

$$\zeta = \frac{-\ln\left(\frac{Pos}{100}\right)}{\sqrt{\pi^2 + \ln^2\left(\frac{Pos}{100}\right)}} \tag{8}$$

By contrast, the proposed method provides better performance and maximum reduction time response to be measured Microsecond unit, providing a magnificent technique to overcome the major previous works in case of the majority of them not accomplish the highest reduction, despite using evolutionary algorithms to solve controller problems as in [42–47].

6. Conclusion

This work presents a very simple analytic tuning procedure, which yields surprisingly superior results and is boosted with improved test bench design. Further, it is well suited to optimize tuning PID parameters. It was proposed a novel technique based on different tuning methods RAT, Z-N, S IMC, CHR, and AMIGO to be combined with optimization SISO application. The performance was analyzed and evaluated in terms of time response specifications, optimal PID gains, and poles zeros location. The time response of all methods and their system characteristics are compared with each other. Further, the designed controller is implemented on a second order system using MATLAB/SISO tool environment. Simulation results demonstrate that all tested tuning based proposed method can enhance the time response considerably, where $\boldsymbol{AMIGO_{OBT}}$ provides greatly improved over existing methods were studied in this paper, particularly for eliminating overshoot and minimization time response. It was proved that using $\boldsymbol{AMIGO_{OBT}}$ can be considered as a novel method to improve the efficiency of the PID controller. The proposed strategy can abolish the drawback in other techniques, next to obtain the best solution to improve the speed performance of the controller. Further providing a capability to improve the robustness, stability, proficiency, besides easily and quickly calculations. The importance of the proposed technique is that the control action provides high precision response and significantly shorten overshoot which is more applicable to be used in a robotic control system for high speed applications. Moreover, it can be used to control a higher order system. Considerably, it gives superb information into how the controller should be returned in response to process changes in terms of proportional gains and time delay. In the scope of the future, it is possible to use this technique with the Genetic Algorithm to optimize the DC motor controller significantly, prepared to configure the hardware on Field Programmable Gate Array System on Chip (FPGA-SoC), using both MATLAB and VIVADO application.

Conflict of interest

The authors declare that there is no conflict interest.

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