Design Techniques Study of PID Controllers

Amin Alqudah[1] and Asseel Qasaimeh[1]

[1] *Computer Engineering Department, Hijjawi Faculty for Engineering Technology, Yarmouk University, Irbid, Jordan*

Abstract: Control system is an essential element of the daily process in modern culture. Control system manages the different appliances (entertainment and environments) and controls the industrial progressions and transportation schemes. Therefore, it controls our land air, sea and space explorations. Digital controllers are used in most applications with microprocessors, computers, and digital electronics. So, each electrical, mechanical or chemical engineer ought to be familiar with the digital controller's basic theory. This paper will study different research techniques about well known controllers; Proportional-Integral-Derivative (PID) controllers. So, it will summarize their structure and their recent developments. After that, new tuning algorithm will be explored using several techniques or change PID controller structure to match several systems' requirements.

Keywords: PID controller, PID tuning, proportinal term, integral term, derivative term.

1. INTRODUCTION

In practical life, every system requires time controlling of its variables. Therefore, different controllers are used to satisfy certain specifications (in transient time and steady-state for example). With experience, controllers have to be used in form of negative feedback, to guarantee good performance of the system in presence of disturbances and uncertainty conditions. Nowadays, with the incessant growth in industry, controllers' using is increasing, since they are responsible to handle regulatory control. Therefore, many studies have worked to develop different type of controllers [1].

Proportional, Integral and Derivative (PID) controllers are the most common type. Since they are used extensively in most industrial applications and they have a robust and optimal performance for large range of systems (like unstable systems, stable systems, linear systems and nonlinear systems).Generally, PID controllers are classified to three types; ideal, parallel and series PID controllers. Practically, ideal PID controllers have realistic difficulties and Inapplicable. Therefore, they are used in academic studies only. The early industrial systems had series transfer function representation. These systems used series PID controllers to maintain the continuity in analogue. However, current PID controllers are digital in parallel form, but series PID controllers are still used in some industrial PID controller

manuals. Parallel PID controllers are extensively used according to their accomplishment ease in both digital and analog forms. The main defects of these controllers are the derivative kicks and proportional kicks. In a turn to reduce these effects, a customized parallel controller structures forms were designed (like ID-P and I-PD controllers) which are the most popular PID controllers [1, 2].

Actually, to run PID controllers correctly, their parameters have to be set accurately. The process of setting these parameters to certain values is known as PID controller tuning and based on the process and characteristics of the system. However, good controller tuning increases system's robustness, but it is costly and time consuming process. Usually, tuning process is directed by multiple tuned loops. But affect on system's performance to make it uneconomic and hazardous [3].

2. RELATED WORK

During last few years, Proportional, Integral and Derivative (PID) controllers were considered as dynamic topic in researches. Because they have been used in most of controlling processes. And they can set satisfactory parameters using small amount of information. PID controllers don't use the whole mathematical model, so they have the less efforts and difficulty than other controllers. Therefore, these controllers are used to reduce the price benefit of acquired mathematical models of systems. In 1940s, PID controllers were considered as

Email: amin.alqudah@yu.edu.jo, asseel_1@yahoo.com

very important element in control processes. Therefore, PID controllers were used frequently in logic, selectors, sequential functions, and straightforward function. These controllers contribute in most complicated computerization system building like energy production systems, transportation systems and manufacturing systems [4].

PID controllers are also used in pneumatic tools, solid state devices and vacuum electronics devices. And now these controllers are used in the digital implementation of microprocessors. Despite the wide use of PID controllers, but they have simple control structures that can be understood easily. This simple structure make operators' plant find the relative parameters tuning quickly [5].

In [6] authors studied the soft switched boost converter design and simulation for a switched reluctance motor using closed loop PID controller. The soft switching system was built to decrease switch's stress and switching loss. Therefore, the output harmonic generations were reduced too.

In [7] authors built logic based supervisor controller. This controller was designed to track 1MW high concentration photovoltaic (HCPV). In this system PID controller was used to track sun position with light sensor which aware the intensity of sun light. Consequently they had used logic-based supervisor (LBS) to allow PID controller to switch to the sun path in cloudy or sunny conditions [7].

To maintain the stability of system that used PID controllers, many improvements were proposed. In [9] the authors combined the linear-quadratic (LQ) regulators with PID controllers to increase his system's robustness. Generally, this combination is good option when the accurate system model is missing. In [8] authors built Linear-Quadratic Regulator (LQG) control system or H-infinity (H∞) control system. Their system is tracking system with high accuracy performance and more robust especially in exogenous disturbance conditions (like the cloud effects or wind gusts) [8, 9].

In [10] authors designed comprehensive circuits that used PID controllers with active elements (like operational amplifier (Op-Amp) and operational transconductance amplifiers (OTA)). Their circuit showed alternative construction using the 2nd generation current conveyer (CCII). This circuit was compared with the classical solutions to show enhanced features (like the symmetrical transfers of reference and feedback paths) [10].

In [11] authors designed field-programmable gate array (FPGA) structure and used it in biomedical applications. They used fuzzy PD and PID controllers in FPGA structure. They tried to develop insulin infusion to diabetic patients using automatic fuzzy logic PD and PID controllers. Diabetes patients need an external insulin source which they infuse the suitable glucose rate.

Therefore, they designed insulin pumps that controlled by automatic Fuzzy PD Controller. Because this controller has high efficiency, superior with the nonlinear inputs and low power consumption with compare to the traditional controller. Therefore, the level of blood glucose was perfectly monitored [11].

In [12] authors built autonomous vehicle's controlling systems which allow driving the car automatically to specific location with certain velocity and time. Autonomous vehicle controlling system is mainly useful to introduce autonomous intersection management protocol which is known as AIM. This protocol showed high accuracy in intersection managements and low delays with compare to stop signs and traffic signals. They used set point scheduling algorithm in their autonomous vehicle controlling systems. This algorithm generates the set points of the parameters of PID controllers which control throttle actuators and brakes. To make the vehicle appears at the desired position through accurate velocity and time. When this system was experimented showed that the breaks a heuristic based set point scheduler which doesn't supply any assurance concerning to the velocity and arrival time. When this system was experimented, results showed that the breaks were based on set point scheduler; therefore the velocity and arrival time weren't accurate. Therefore, they presented a set point scheduler basing on an extra sensible model of vehicle control scheme. This model was built using an empirical performance PID controllers profiling for vehicle's throttle actuators and brake. They also improve their model using developed smoothing technique that compute set points sequence. To make the vehicle slow down elegantly with no need to hit the brake strongly. With the comparison between the set point scheduler implementation in autonomous vehicle system with the default vehicle's using reactive PID controller, their system outperformed the default system in its accurate velocity and arrival time [12].

In [13] authors designed controller to control the output power in micro turbine system. Their system is considered as the most important distributed generation system where the load is continuously varied. Therefore, they employed PID controller with optimized coefficients, to control output power against the variations of load. They used particle swarm optimization algorithm (PSO) to optimize PID controller coefficients. In other words, they simulated PSO algorithm many time using different loads to determine the efficiency of the controller.

At the same year, in [14] authors designed multipurpose performance criterion (MPPC) that used PSO algorithm in PID controller parameters optimization process. In this system PID controller controlled the temperature of exhaust's gas in turbine system. Because the performance of PID controllers depends on its

parameters, they tuned them using PSO algorithm (which is called PSO-PID algorithm) which superior the conventional PID controller tuning that employs the Ziegler-Nichols technique. In time domain, PSO-PID controller's performance (which measured through the rise time, the maximum overshoot, the absolute error (AE) and the settling time) are optimized according to the MPPC criteria. Practically, the short transient time with limited temporal peaks of the main parameters is necessary to design good system. In this system, gas turbine was suffering from unwanted transient response when load was changed (like system's startup, shutdown and some abnormal conditions). In spite of the extensive using of PID controllers, they have some weaknesses like low efficient tuning method. In their system, control loop dynamical controlled the temperature of exhaust's gas. Therefore, the operating conditions of the system and the whole loop performance were changed. These changes were resulted by the nonlinearities processes in aging process, control channel, production properties of raw materials, strategy changes, and equipment maintenance cycles changes [14-16].

In [17] authors proposed novel technique to tune the I-PD controller; they used the time delayed unstable process (TDUP) with Bacterial Foraging Optimization (BFO) algorithm. In this system, the tuning process was used to hunt optimal parameters of the PID controller (which are K_p, K_i, K_d) during different criterions. They studied the cost of multiple functions; like the Integral Absolute Error (IAE), the Integral Squared Error (ISE), Integral Time weighted Absolute Error (ITAE) and the Integral Time-weighted Squared Error (ITSE). After that, they simulated their BFO-based I-PD tuning technique to validate algorithm's performance. The results demonstrated that the tuning process is an independent model. It provided an improved performance for the set point tracking.

3. PID CONTROLLER

As mentioned before, PID controllers are the most common feedback controllers. They were considered as essential elements and important ingredients of the distributed control system. Today, more than 95% of the control processes use PID controllers. Through years, PID controllers have different forms to survive through the rapid changes in technology (like mechanics and pneumatics changes and the changes in microprocessors architecture from electronic tubes to transistors and integrated circuits). Practically, microprocessors have had a large influence on the PID controller. Therefore, all PID controllers' designs are based on microprocessors. They make some opportunities to add additional features (like gain scheduling, automatic tuning and continuous adaptation) [18, 19].

Till now, researchers presented different forms of PID controllers using different devices (like operational transconductance amplifiers (OTA), second generation current conveyer (CCII), or CDTA). These devices tune controllers' parameters independently. In spite that these PID controllers have high complexity and large power consumption, they maintain high efficiency and low cost [10].

Actually, PID controllers are used as standalone block with single input single output (SISO) system. As shown in Figure 1.
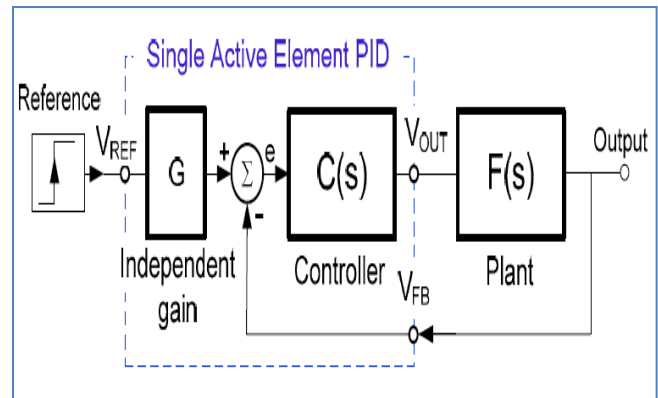

Figure 1: SISO system with a single PID controller [10]

From Figure 1, notice that PID controller contains:

- Differential blocks
- Transfer function $\left|\frac{V_{OUT}}{V_{REF}}\right| = G * |V_{OUT}/V_{FB}|$
- Independent gain (G)

The transfer functions of PID controllers can be determined using different ways [20]. Generally, their transfer function has denominator part and numerator part. From the electrical view, ideal PID controller has two zeros of its numerator and a single pole in the origin. This makes its frequency gain reach the infinity. Therefore, ideal PID controllers are unrealizable, however this controller can be used with derivative filtering that has an identical denominator and numerator orders. PID controllers are written through the following transfer function:

$$C(s) = k\left(1 + \frac{1}{T_i s} + \frac{T_d s}{\alpha T_d s + 1}\right) \qquad (1)$$

where T_i and T_d are the time constants of the integrator and the differentiator, respectively. While α is the filtering factor, and k is the gain [21].

Figure 2 will show the performance of ideal PID controller with derivative filter which has infinite bandwidth in ideal conditions. Actually their bandwidth is limited, because they used operational amplifier which has limited bandwidth.
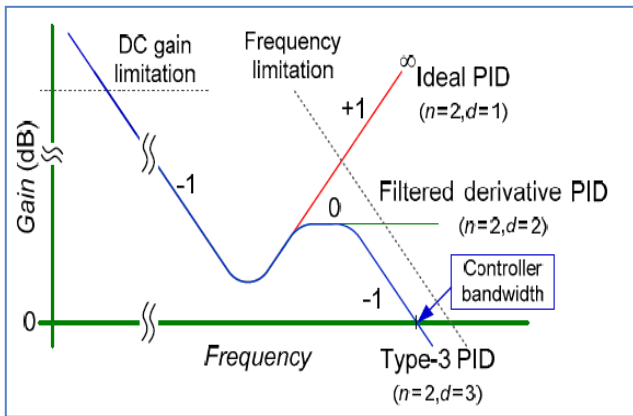
Figure 2: PID controller Frequency transfers [10]

Generally, all controllers can be written in form of:

$$C(s) = K \frac{\left(\frac{s}{z_1} + 1\right)\left(\frac{s}{z_2} + 1\right)}{\left(\frac{s}{p_1} + 1\right)\left(\frac{s}{p_2} + 1\right)} \qquad (2)$$

where $p_1 = p_2 = \infty$ matches the ideal PID parameters, $p_1 < \infty$, $p_2 = \infty$ matches the derivative filtered controller and $p_1, p_2 < \infty$ matches additional first-order lag controller.

Nowadays, the modern studies on PID controllers' developments suggested using fuzzy logic in their designs. To explore the new PID controllers' designs; Fuzzy PID controller and hybrid fuzzy PID controllers are explored through the next sections [22].

A.   Fuzzy PID Controller

The logical system that is nearer to the human thinking spirit and usual language than the other traditional logic system, these systems are known as the Fuzzy logic systems. The Fuzzy controllers are measured as a novel process that lies between the human like decision making and conventional mathematical control [11].

Ackerman .et al [21] utilized the both compartment model that represent the glucose and insulin concentration dynamics in human blood system. This procedure was depending on compartmental system. One of this technique features is that the designation of the model was derived from a physiology understanding. In case of nonlinear inputs, the Fuzzy PID Controller applies improved behavior with compared to the traditional controller.

The determinations of Fuzzy sets are normally performed through an initial system providing with manual data set that fed through the operator. K.H.Kienitz and T.Yoneyama [27] recognized the Fuzzy system that system can add a further enhancement through the adaptive control wherever the gain and time

constant are differed to self tune the controller at different operating points.

B.   Hybrid Fuzzy PID Controller

As PID controllers are regarded as standard control devices in control systems and fuzzy controllers have positioned themselves as the classical PID controllers' counterpart. However, the classical PID controllers work perfectly in linear systems with preferable cost and benefits, but they face many difficulties with the nonlinear parameters which affect on their performances. Fuzzy controllers can be applied successfully in linear and non-linear systems, because they have knowledge which is based nonlinear characteristics.

In [21] authors designed the first fuzzy PID controller; they used the compartment model to represent the glucose and insulin concentration dynamics in human blood. Their system depended on the compartmental system while its features were derived from the physiology understanding of human system. This system had linear and nonlinear inputs and the fuzzy PID controller applied an improved behavior when it's compared to the traditional controller. The testing of Fuzzy controller was performed using initial parameters and manual data set that fed through the operator.

In 1990's, Fuzzy system and PID controller hybridization was studied and various hybrid structures have been arisen in literature like Kwok et al. study in 1990, Brehm and Rattan study in 1993, Li study in 1998 and Li et al. study in 1999. Some studies combined these two control structures with switch in this system, the switch combined fuzzy controller with conventional PID controllers to achieve smooth control [23- 26].

In [27] authors studied Fuzzy system and defined it as system that can enhance PID controllers using adaptive control. In PID controller, Fuzzy system changes the constant gain and time to make the controller tune itself at different operating points.

Naturally different structures of hybrid controller have been presented previously [28]. The design of the original hybrid fuzzy PID controller improves the system to have an advanced response performance with both states; the steady states and transient. Fuzzy PID controllers were classified to three different types which are the direct action type; the fuzzy gain scheduling type and hybrid type fuzzy PID controllers [29, 30].The direct action type were classified to three types depending to the number of inputs. Direct action fuzzy PID controller's types are the single input, double input and triple input controllers. These fuzzy PID controllers' classifications are illustrated through the Figure 3.
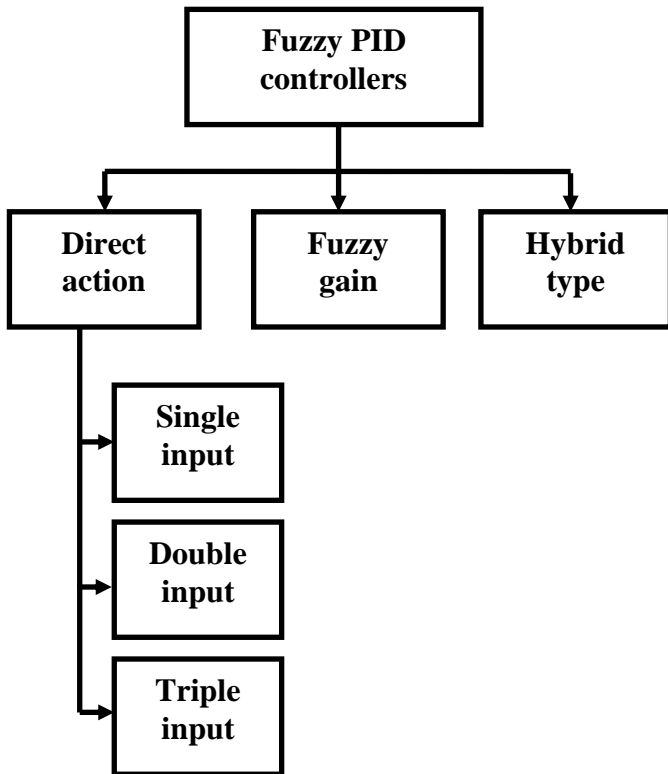
Figure 3: Fuzzy PID controllers Classification

The hybrid controller is shown in Figure 4. Hybrid controller owns two major parts that the fuzzy PID and classical PID controllers.
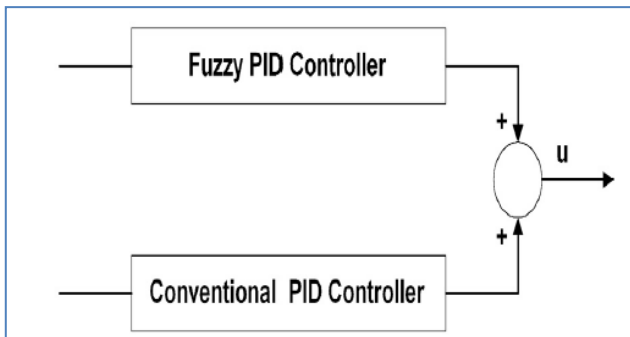

Figure 4: Hybrid fuzzy PID controller Block diagram [29].

The standard PID controller is called the three terms controller which has transfer function as shown in equation 3:

$$G_{PID}(s) = K\left(1 + \frac{1}{T_I s} + T_D s\right) \qquad (3)$$

where K is the proportional gain, T_D is the derivative time constant and T_I is the integral time constant. The three term functionalities are emphasized through:

i. The proportional phrase is presenting the overall control action relative to the error signal during the all-pass gain factor.
ii. The integral term decreases the errors through steady state of the low frequency compensation through the integrator.
iii. The derivative term can improve the transient response during the high frequency compensation through the differentiator.

4. PID CONTROLLER TUNING

Tuning PID controller is the process of setting its gains based on certain characteristics of the system it controls. It is usually time consuming and costly, because it might be resulting in numerous tuned loops. This would result in an unwanted inefficient performance, which could be dangerous and not viable as well [1,13].

Actually some of these methods are quite old and back to 1950's. however they are still widespread in use like Ziegler-Nichols oscillation method where in this method is valid for open loop and stable plants, Ziegler-Nichols reaction curve method where the linearized quantitative version of a simple plant can be obtained with as open loop experiments and finally the Cohen-Coon reaction curve method which carried out the further studies to find controller settings which based on the sane model lead to a weaker dependence on the ratio of delay to time constant.

There some new approaches that tried to optimize PID controller parameters through several techniques like; The Particle swarm optimization (PSO) was used in many optimization problems resolving which was proposed by in [30]. While in [17] authors proposed a novel method to tune the PID controller structure for the time-delayed unstable process (TDUP) using Bacterial Foraging Optimization (BFO) algorithm. The tuning process is focused to search the optimal controller parameters (Kp,Ki, Kd) by minimizing the multiple objective performance criterion [17].

A. Particle Swarm Optimization (PSO) algorithm

Particle swarm optimization (PSO) is considered as one of the earlier developments in the combinatorial met heuristic optimizations category [31]. Within PSO algorithm, every individual is submitted like a particle and symbolizes an applicant solution to the optimization trouble [31].

Primary, random solutions' population ''particles'' are composed in D dimension space where every particle considered as a solution. The i_{th} order particle can be

represented through $X_i = (x_1, x_2, \ldots, x_{iD})$. every particle's situation can be changed through the subsequently stage and the finest situation can be decided through fitness function. When the fitness functions has the minimum rate then it is recognized by the finest situation and save it inP_{besti}.

PSO's overall version keeps general best rate (g_{best}) track with its location that obtained through particles population [32]. PSO contain many steps, when each particle's velocity is changed toward its P_{best} and g_{best} depending on the following equation.

$$v_{id} = \omega * v_{id} + c_1 * rand_0 * (p_{id} - x_{id}) + c_2 * rand_0 * (p_{gd} - x_{id}) \quad (4)$$

The i particle velocity can be represented by $V_i = (v_{i1}, v_{i2}, \ldots, v_{iD})$. the acceleration is weighted through a random term, with divided random numbers being created to accelerate toward P_{best} and g_{best}. The i_{th} position of the particle is updated corresponding to the following equation [33]:

$$x_{id} = x_{id} + cv_{id} \quad (5)$$

where, P_{id} and P_{gd} are P_{best} and g_{best}, c_1 and c_2 are constant values, T is determined by:

$$\omega = \omega_{max} - \frac{\omega_{max} - \omega_{min}}{Iter_{max}} * Iter \quad (6)$$

where ω_{max} and ω_{min} are the maximum and minimum ω value respectively. At the first ω establish with great value while at the end of problem ω value is the minimum value. By PSO algorithm using to regulate controller parameters during much of improvement in controlling systems and making controllers applicably, in some power system, effortless controllers are the most desirable controllers. Generally in power systems, PID controllers are the compensators since PID controllers are easily implemented in both systems; digital and analog.

PID controller can be used to control load's voltage in voltage system and the general schematic of the controller can be seen in Figure 5.

The general form of this controller can be expressed using the following equation. The parameters of the controller (k_p, k_i, k_d) have to be optimized. The design of the controller isn't practical to be implemented since this controller is an absolute nonlinear system:
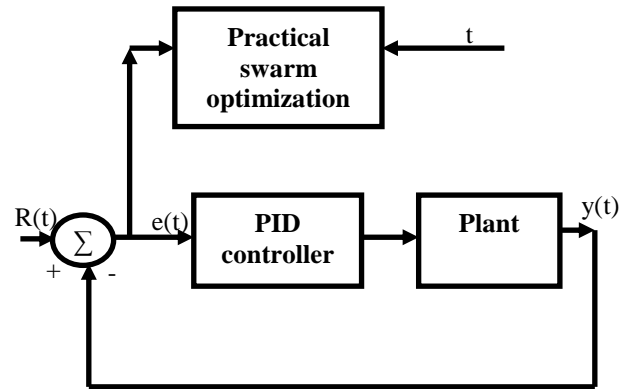
$$G_c(s) = k_p + \frac{k_i}{s} + k_d s \quad (7)$$

Figure 5: General schematic of the controller

Sequentially to design controller using PSO for the power system, the load is considered in the worst condition. Now, the selecting objective function has the most importance in optimization process. Since the different objective functions choosing can totally change the variation state of the particles, so in optimization problem the error signal have to calculate through the following equation:

$$j = \int_0^{t=t_{sim}} |p_{ref} - p_{load}| \, dt \quad (8)$$

where, t_{sim} is the simulation time where the calculation of the objective function is done.

B. Unstable System I-PD Controller Tuning using Bacterial Foraging Algorithm

The algorithm of Bacteria Foraging Optimization (BFO) is a novel class of biological and stochastic overall search system that based on bacteria foraging behavior mimicking which the locating and ingesting food methods. Throughout foraging process the bacterium can show two singular actions which are swimming or tumbling. In tumbling action bacterium changes its orientation while during swimming bacterium move its direction [17].

So, after several numbers of whole swims, the finest half population suffers the reproducing and the rest of the population will be eliminated. The elimination spreading result is performed where bacteria are randomly liquidated with very little probability [34-36]. Figure 6 illustrates the Bacteria Foraging Optimization algorithm's flow chart.
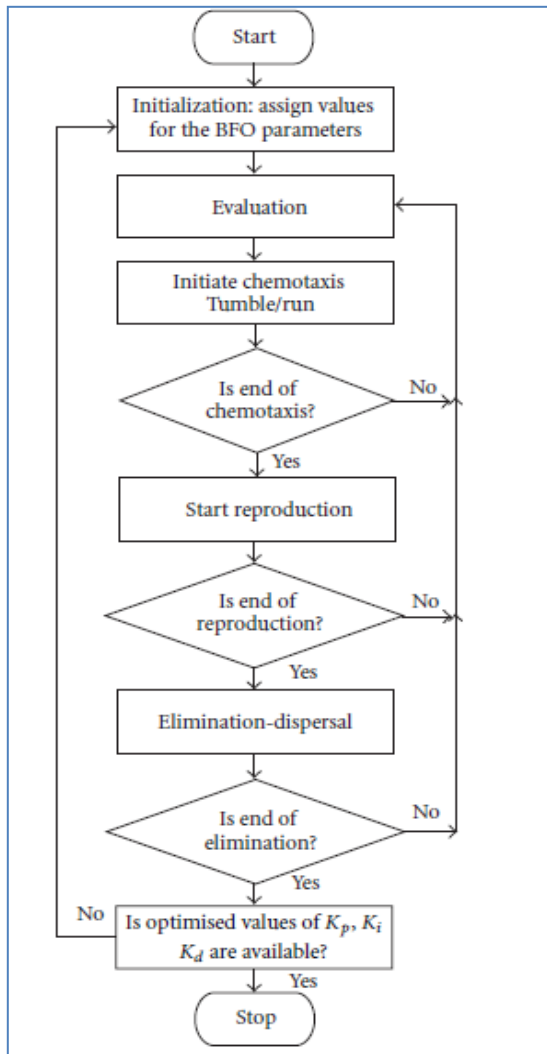
Figure 6: BFO flow chart [17]

C. I-PD Controller Tuning Procedure

PID controllers are utilized in the industrial processes in order to improve responses in steady state and transient of the plant. Through closed loop control system consideration, the $G_p(s)$ is under control process while $G_c(s)$ is the controller as shown if Figure 7.
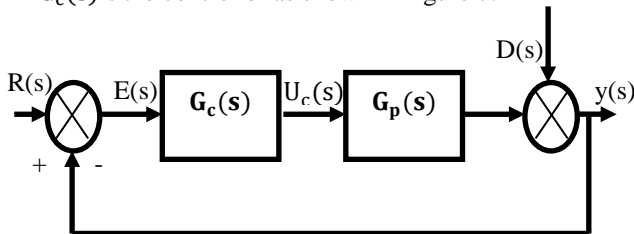

Figure 7: Close loop system block diagram

In this system the main aim is to formulate $Y(s) = R(s)$. So the controller constantly adjusts $U_c(s)$ value of the error $E(s)$ which is zero regardless to the disturbance

signal $D(s)$, and $G_c(s)$ is a simple or modified PID controller.

The non interacting I-PD controller structure form can be shown as Figure 8 where its output signal of the I-PD controller can be expressed by:

$$U_c(s) = K_i \int_0^T e(t)dt - \left[K_p y(t) + K_d \frac{dy(t)}{dt} \right] \qquad (9)$$

where integral term (K_i) takes action for the error signal $e(t)$. With any sudden change in the reference input, no affect will be happened in the derivative (K_d) and proportional (K_p) terms, as these terms efforts on the process output $y(t)$.

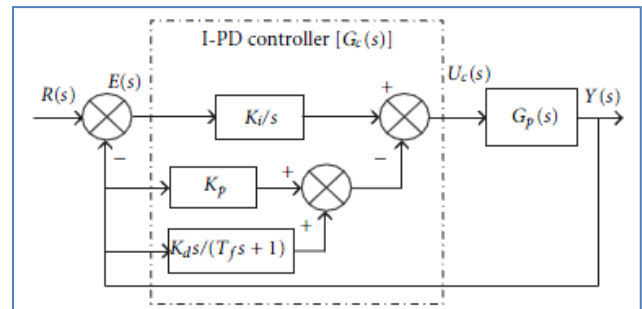
Figure 8: Parallel I-PD control system structure [17]

In the closed loop systems it is important to make the peak overshoot (M_p), final steady state error (E_{ss}), and settling time (t_s) as small as achievable. So, throughout the optimization exploring, it is essential to allocate the necessary values for M_p, E_{ss} and t_s. Where M_p is the reference input "and the maximum process output difference , t_s is the required time of output to reach the final steady state value and E_{ss} is the error $e(t)$ value when time goes to infinity. Cost Function (CF) can guide BFO algorithm to hunt the optimized parameters of the controller. The following equations show them:

$$IAE = \int_0^\infty |e(t)|dt = \int_0^\infty |r(t) - y(t)|dt \qquad (10)$$

$$ISE = \int_0^\infty e^2(t)dt = \int_0^T [r(t) - y(t)]^2 dt \qquad (11)$$

$$ITAE = \int_0^\infty t|e(t)|dt$$

$$= \int_0^T t|r(t) - y(t)|dt \qquad (12)$$

$$ITSE = \int_0^\infty te^2(t)dt = \int_0^T t[r(t) - y(t)]^2 dt \qquad (13)$$

Where $e(t)$ is the error and $r(t)$ is the reference input while $y(t)$ is process output. The performance criterion is:

$$J_l(k_p, k_i, k_d) = (w_1 . CF) + (w_2 . M_p) + (w_3 . t_s)$$
$$+ (w_4 . E_{ss}) \qquad (14)$$

The process of tuning aims to find the optimal k_p, k_i, and k_d values through space search which can minimize the J_l function. Figure 9 demonstrates the essential block diagram of the BFO algorithm to tuning I-PD controller where the performance criterion of $J_l(k_p, k_i, k_d)$ directs the BFO algorithm to obtain the appropriate values of the controller parameters.
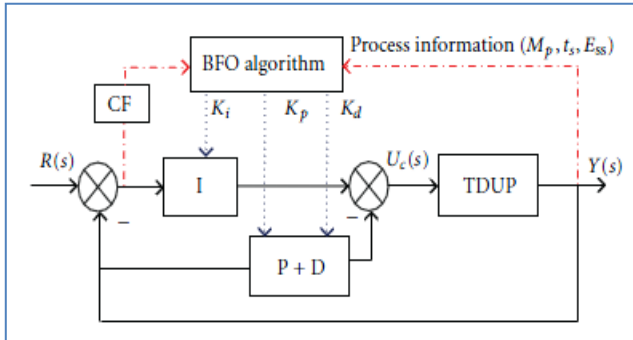

Figure 9: I-PD controller tuning using BFO algorithm system [19]

Previous of the optimization search, it is essential to allocate the next algorithm parameters. Search space Dimensions which are the number of bacteria, the number of swimming step, the number of reproduction steps, swim length; elimination-dispersal number; bacteria reproduction and finally elimination dispersal probability value. In the previous work, there is no direct line to assign BFO algorithm tuning parameters.

5. CONCLUSIONS

In every system in daily life control systems have the essential part of them to manage its different appliances and environments. In general, digital controllers are used in all almost applications in corporate with other essential devices like microprocessors, computers, and digital electronics. Then, we can found digital control system in electrical, mechanical or chemical applications systems.

In this paper a survey study of PID controllers were introduced to explore their structures with the most recent development whether in PID controller tuning process or on their structure modifications.

Many studies were implemented to improve PID controller performance using several methods and they achieve remarkable results.

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Amin Alqudah received his MSE and Ph.D. in Electrical Engineering from the University of Colorado at Denver-USA in 2005, and Colorado State University-USA in 2009, respectively. Since 2009, he has been working with the Department of Computer Engineering, Yarmouk University-Jordan. He is currently an Assistant Professor. His research interests include artificial intelligence, pattern recognition and image processing.

Asseel Qasaimeh received her BSc degree in Electronics Engineering from Yarmouk University-Jordan in 2010. She is doing her MSc degree in Computer Engineering-Industrial Engineering in Yarmouk University. Since 2010, she has been working with the Department of Computer Engineering as Teaching Assistant/Laboratory Instructor, Yarmouk University-Jordan. Her research interests include Electronics design, digital control and image processing.