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A Swarm Based Integer and Fractional Order Heart Rate Controller for Cardiac Pacemaker

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Abstract: - The heart's significant contribution is well known in the functioning of the human body. If it stops operating, the body shuts down systematically, which is known as cardiac arrest. The heart acts as a power supply that generates the electrical pulses which run through the entire body to supply energy to every organ. But in today's time, due to our unhealthy lifestyle, the functioning of the heart gets uneven, that it is unable to supply the regulated electrical pulses. This irregular supply of electrical pulses is known as arrhythmia. In order to overcome arrhythmia, the medical device pacemaker is invented to control the irregularities of the heart rate. The pacemaker generates the electrical pulses artificially when the heart is unable to respond at regular intervals. Many researchers have proposed several control techniques using PID controllers to improve the performance of such device called as artificial pacemaker. In this work an optimized system is designed for an artificial cardiac pacemaker to well perform so that the system can generate a controlled desire response through the incorporation of both integer and fractional order PID controller for better system performance with least errors. The applied integer and fractional order PID controllers are tuned using various classical tuning methods and the modern optimization technique such as particle swarm optimization (PSO) method to obtain a response with better dynamic and static performance. These implemented tuning methods offer a good control characteristic for the pacing rate of the cardiac pacemaker.

Keywords*:* - Cardiac pacemaker, Conventional tuning methods, Integer and fractional order PID controller, Particle swarm optimization.

I. Introduction

In the fast-moving cities, the cardiovascular diseases are the most common and distressful disease. However, in many developing nations, it becomes deadliest due to the unhealthy lifestyle of its people [1]. Each part of our body generates an electrical signal that can be analyzed to determine the performance of the body organ. Among these different electrical signals, the heart rate can be measured by electrocardiogram (ECG). In normal circumstances the Sinoatrial (SA) node involves the heart rate regulation. This SA node is also known as a natural pacemaker of the body that generally controls the pacing of the heart when it finds any irregularity in the heart rate. But it is found that due to the lifestyle or some other physiological conditions, the natural pacemaker does not perform well, and the heart rate becomes too slow, fast or irregular. In that condition, the artificial pacemaker is required to control heart rhythms efficiently [2-3].

In recent past years, many researchers have proposed a cardiac system with controllers to improve the performance of the artificial pacemaker [4-5]. To develop this proposed system the Proportional Integral Derivative (PID) controller is used widely due to its basic structure [6]. There is a wide scope to work on PID controllers as they are available in integer as well as fractional order [7]. Two more degrees of freedom are available for the fractional-order controller that increase the response of the system [8]. Additionally, numerous tuning methods for integer and fractional order controllers are available in the literature that can be used with the system [9]. To improve heart rhythm disorders a standard implantable medical electronic device is applied to cardiac patients which is known as pacemaker. This device aims to provide better healthcare by managing and treating irregular heart rates [10]. The cardiac pacemaker generates an essential externally stimulated signal for the heart to regulate the interrupted heart rate. This action becomes crucial to save the cardiac patients life by reducing the risk factor. Hence for cardiac treatment, the pacemaker has become one of the most important implantable devices [11-12].

Based on consequences that arise due to various activities and conditions such as lifestyle, physiological changes due to exercise, emotional status and variable environmental situations, several types of sensors can be used to design the cardiac pacemaker [13]. For better accuracy, dual sensors are used to design the cardiac pacemaker which makes the system robust and provides precise results. By double-checking the results, these dual sensors in the pacemaker compensate for each other's performance [14-15]. In a pacemaker, the controller is used as the main component that provides the controlled output response which is an error signal obtained by the difference between the heart rate's actual value and the desired set point. Now, this error signal is further controlled to regulate and restore the normal heart rate response to achieve the set point [16]. In this paper, the existing cardiac pacemaker system is simulated on MATLAB/Simulink from a very initial level to analyze the system performance and after that controlled integer and fractional order PID controllers are applied to verify the improvement in the response.

This paper is organised as follows in the remaining section. In Section 2 related work and methods is discussed for the Integer and fractional order PID controller with their conventional and modern optimization methods and basics of cardiac

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pacemaker. The experimental results and discussions of existing system and its comparison with the proposed cardiac pacemaker system are provided in Section 3. Section 4 discusses the conclusion.

II. METHOD

This section includes the study of PID controller and its type i.e. integer and fractional order controller. The proper tuning of PID controller is important before applying it with any system. Hence, various conventional and modern optimization techniques are adopted for the tuning of PID controller are discussed in this section. Also, the mathematical equations for the heart and pacemaker system is described in this section.

A. Classical and Fractional PID Controller

Although there are many different types of controllers available, the PID controller is one of the simplest to utilise with a cardiac pacemaker [16]. PID controllers are often employed in many different industrial applications [17-18]. They are set up in a closed-loop configuration with feedback and its result is the difference of actual heart rate and desired set point as shown in Figure 1. There are various types of PID controller as discussed in sub section.

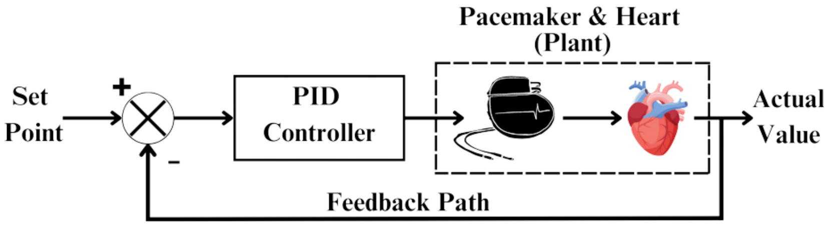


Figure 1. Close loop arrangement of cardiac pacemaker and heart with PID controller.

Proportional, Integral and Derivative is the acronym for the PID. These three actions are combined to form the PID controller as shown in Figure 2. All the three combination proportional, integral and derivative has their significance which varies the control characteristics of the system [19]. The proportional, derivative and integral action is responsible for approaching the desired set point, include the accumulation of previous errors and the system's rate of change of error respectively. By summing these three terms, the PID controller calculates the control signal and applies it to the system. A PID controller's main objective is to reduce the disparity between a set point and a system's actual output by continuously modifying a control signal [20]. In general, the PID controller is a flexible control method that works well with a wide range of systems and applications.

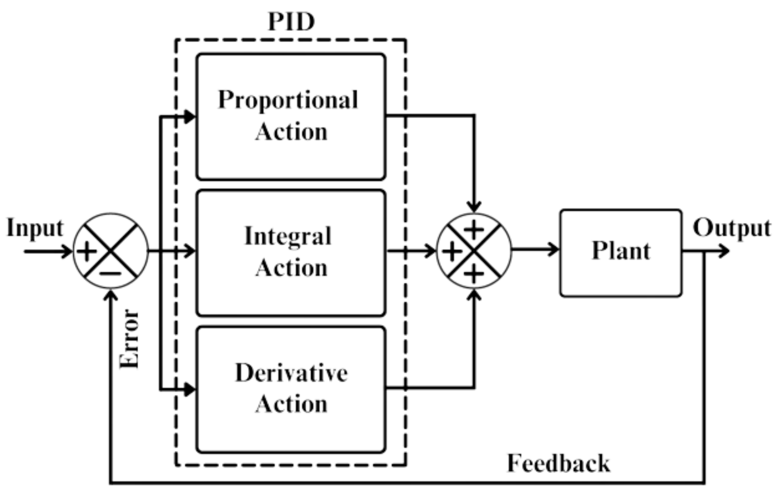


Figure 2. Structure of a Traditional PID Controller.

The following equation describes how the PID controller processes the error signal, e(t), and produces its response, u(t) in time domain

$$u(t) = K_p\, e(t) + T_i \int_0^t e(t)\, dt + T_d \frac{d}{dt} e(t) \tag{1}$$

and it is described by its transfer function as

$$C(s) = \frac{U(s)}{E(s)} = K_p + T_i/s + T_d s \tag{2}$$

Where,

K_P: Proportional gain,

T_i: Integral action time or reset time and

T_d: Derivative action time or rate time.

E(s): Error signal's Laplace transform; e(t)
U(s): Control signal's Laplace transform; u(t)
Fractional order PID controllers are a relatively new and emerging class of controllers that are gaining popularity in various engineering applications and proposed by Podlubny in 1999 [21]. The concept behind a fractional order PID controller is to employ fractional calculus, an extension of conventional calculus, to create controllers that can offer higher performance and more flexible control over a system [22].
The proportional, integral, and derivative gains are all integer values in a conventional integer-order PID controller. However, a PID controller with fractional order can have gains that are fractional values, giving it additional flexibility to modify how it responds to the system it is controlling [23] as shown in Figure 3. The fractional order PID controller can be designed using different methods, such as fractional calculus-based approaches or optimization-based approaches [24].

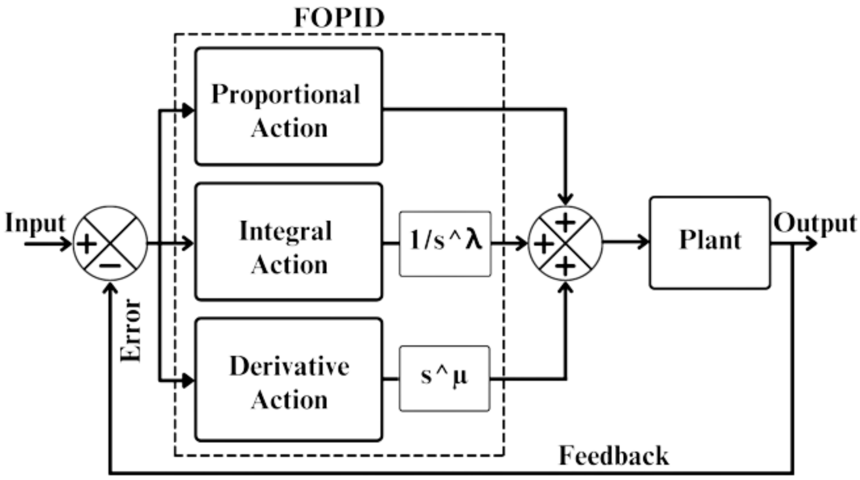


Figure 3. Schematic of Fractional PID Controller.

Utilising a fractional order PID controller has the benefit of better control over nonlinear and complex systems that cannot be accurately modeled using traditional integer-order models [25]. Additionally, fractional order PID controllers can provide better performance and faster response times compared to traditional PID controllers in some applications [26]. Despite their advantages, designing and implementing fractional order PID controllers can be challenging and requires a good understanding of fractional calculus and control theory [27]. Nonetheless, with the growing interest in this field, fractional order PID controllers are expected to become increasingly popular in various engineering applications in the near future [28]. A generalisation of the traditional PID controller is the fractional-order PID (FOPID) controller and its transfer function can be defined as [29]

$$u(t) = K_p\, e(t) + K_i\, D^{-\lambda}\, e(t) + K_d\, D^{\mu}\, e(t) \quad (3)$$
$$C(s) = \frac{U(s)}{E(s)} = K_p + K_i\, s^{-\lambda} + K_d\, s^{\mu};\ (\lambda,\ \mu > 0) \quad (4)$$

Where,
K_P, K_i and K_d: Proportional, Integral and Derivative gain respectively,
λ and μ: Fractional orders of integration and differentiation; λ and $\mu \in (0, 2)$
Hence, compared to their counterparts of integer order, the FOPID offers more design flexibility and can be tuned to be more robust due to its two additional parameters λ (lambda) and μ (mu) [30].

B. Modeling of Heart and Cardiac Pacemaker

The heart, which pumps blood throughout the circulatory system, is a crucial organ in the human body. It is in charge of eliminating waste products like carbon dioxide from the body and giving oxygen and nutrition to the tissues and organs. There are four chambers in the heart: the right and left atria, and the right and left ventricles. The electrical system of the heart governs the rhythm and rate of beating. The electrical impulses that drive the heart to contract are initiated by the sinoatrial (SA) node. When the heart's natural electrical system is not functioning properly, and the heart is unable to beat at a regular pace then the artificial pacemaker is implanted to the patient [31].
A pacemaker is a tiny electrical circuit that is inserted under the skin, typically in the chest area, to control the heartbeat of persons who have an irregular or sluggish heartbeat (arrhythmia). It consists of two main parts: a generator, which contains the battery and electronics circuit, and one or more leads, which are thin wires that connect the generator to the heart. Depending on the patient's requirements, pacemakers can be configured to deliver electrical impulses at various rates. They can also keep an eye on the activity of the heart and modify the pacing rate accordingly. Following some are the situations given in Table I in which artificial pacemaker is suggested [32]:

Table I. Application of pacemaker in various conditions.

Condition	Description	Symptoms
Bradycardia	A condition in which the heart beats too slowly, typically less than 60 beats per minute.	Fatigue, dizziness, fainting
Heart block	A disorder occurs when the electrical signals that regulate the heart pace are delayed or blocked as they pass through the heart's chambers.	Fatigue, dizziness, fainting
Sick sinus syndrome	A condition in which the SA node, the heart's natural pacemaker, is not operating properly.	Heartbeat that is too slow, too fast, or irregular
Heart failure	A condition in which the heart is unable to pump blood effectively.	Shortness of breath, fatigue, swelling in the legs and ankles

The overall objective of a pacemaker is to assist in heartbeat regulation and enhance quality of life for people who suffer from heart rhythm abnormalities.

Now, the mathematical modeling of the heart and pacemaker involves generating mathematical equations and software simulations to study their function and behavior. From straightforward electrical circuit models to intricate computational fluid dynamics models, a variety of models are employed to explore the heart and pacemaker [33].

The Hodgkin-Huxley model is a frequently employed mathematical representation of the heart and pacemaker, which discusses how excitable cells, such cardiac and pacemaker cells, produce and spread action potentials [34]. The FitzHugh-Nagumo model, a simplified variant of the Hodgkin-Huxley model uses just two variables to explain the electrical activity of the cells [35].

In addition to these models that describe the electrical activity of the heart at the cellular level, there are other models that describe it at the tissue and organ level. The study of the heart and pacemaker using patient-specific modelling has gained popularity in recent years which includes the data of an individual patient [36].

A straightforward transfer function based model of the heart and pacemaker is taken into consideration in this work. The pacemaker is considered as a low pass filter, permitting various lower frequency excitations while rejecting higher frequencies, as evolved in a living organism's regular metabolic process for the proper operation of the cardiovascular system. Its transfer function is given as [37]:

$$G_P(s) = 8/(s+8) \tag{5}$$

The cardiovascular system can be characterized as an under damped second order system that permits the parametric values for the damping factor and the natural frequency, allowing the heart to function normally. Hence, the transfer function of the heart is given as [37]:

$$G_H(s) = 169/(s^2+20.8s) \tag{6}$$

Cardiac pacemaker research is a rapidly evolving area of research that focuses on enhancing the performance, design, and clinical application of pacemakers [10]. Figure 4 shows the cardiac pacemaker's closed-loop circuitry that illustrates the heart rate control model, which includes the controller, pacemaker, and heart. The actual and desired heart rates are represented in the figure by R(s) and Y(s) respectively while $G_P(s)$ is the transfer function of pacemaker and $G_H(s)$ is the transfer function of the heart.

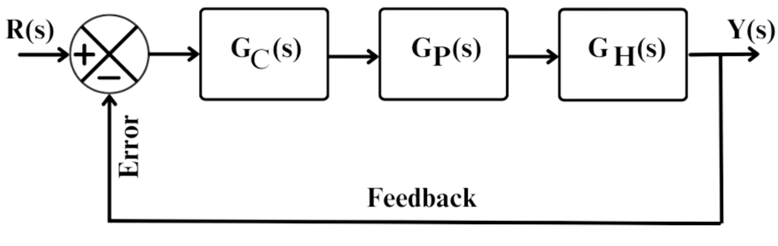


Figure 4. Block diagram of cardiac pacemaker with controller.

C. Control Strategy and Tuning

It is necessary to use a variety of designing strategies to choose the control parameters that will meet the closed-loop system's transient and steady state requirements while creating the mathematical model of the cardiac pacemaker. Controller tuning is the process of choosing the controller parameters to match predetermined performance requirements [38]. The fine tuning of a PID controller involves adjusting the three parameters: proportional gain (K_p), integral gain (K_i), and derivative gain (K_d) to achieve the required result. Different tuning methods are described in subsection.

Based on experimental step responses and the value of the proportional gain that results from the marginally stable system, Ziegler and Nichols proposed two principles for adjusting PID controllers [39]. By giving the plant a unit step of input, the system response is empirically determined in the first method as shown in Figure 5. This method is applicable only if the response of the unit step plant exhibits an S-shaped curve, otherwise the second method is applicable [40-41].

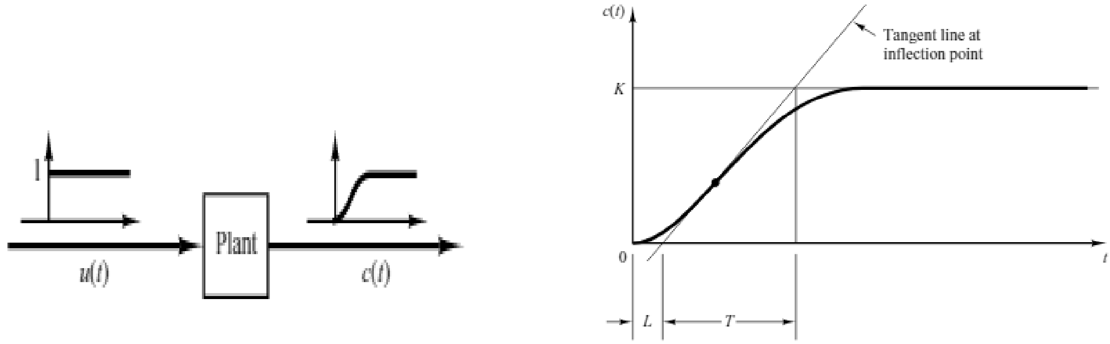


Figure 5. Process Reaction Curve Method.

In the second rule as shown in Figure 6, Only proportional action can be used, and the gain is raised from 0 to a critical point at which the system's output first displays sustained oscillations. This method allows for the experimental determination of the critical gain and period, which aids in determining the controller parameters. Additionally, Cohen and Coon presented a method for fine-tuning the PID controller that involves figuring out the initial values of K_p, K_i, and K_d by examining the system's reaction after performing a step test. These values are then adjusted using a set of correction factors to achieve the desired response [42].

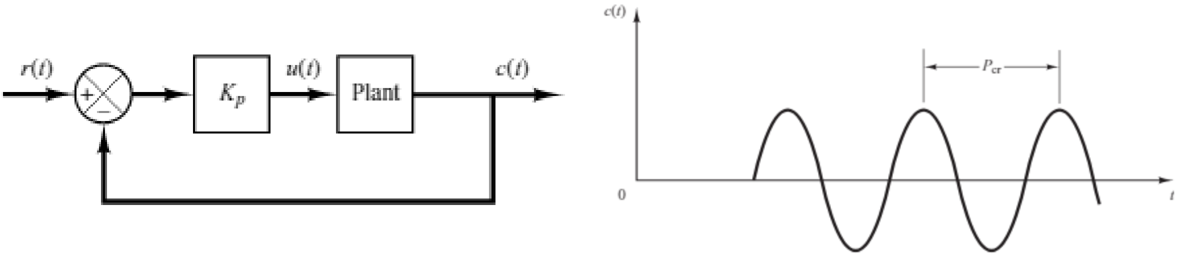


Figure 6. Sustained oscillation method.

The values of the control parameters K_p, K_i, and K_d must be determined in order to tune the PID controller. Now in this study, the cardiac pacemaker system is subjected to proportional action, and the measures that were taken to determine the critical values of gain and time period are as follows [42]:

i. Set the integral time constant (T_i) infinite and the derivative time constant (T_d) to zero.
ii. The proportional gain (K_p) should be increased until the system oscillates with a sustained amplitude.
iii. Now measure the critical gain K_{cr} and critical period of oscillation P_{cr}, which is estimated as:
 $K_{cr} = 3.5446152$ and $P_{cr} = 0.48$ sec.
iv. These values of K_{cr} and P_{cr} are sufficient enough to find out the control parameters of the PID controllers using formula of various conventional tuning methods as given in Table II [43]:

Table II. Various conventional tuning methods for PID controller.

S. No.	Methods	Parameters		
		Kp	**Ti**	**Td**
1	Ziegler Nichols (ZN)	0.6 Kcr	Pcr/2	Pcr/8
2	Modified Ziegler Nichols (MZN; No Overshoot)	0.2 Kcr	Pcr/2	Pcr/2
3	Modified Ziegler Nichols (MZN; Overshoot)	0.33 Kcr	Pcr/2	Pcr/3
4	Tyres and Luben (TL tuning)	0.45 Kcr	2.2 Pcr	Pcr/6.3

v. K_i and K_d can also be determined using the appropriate formula provided in equation (7) and (8) to tune the PID controller after determining the values of K_p, T_i, and T_d [44].

$$K_i = K_p/T_i \quad (7)$$
$$K_d = K_p.T_d \quad (8)$$

vi.The PID controller can now be fine-tuned using all the control parameters.

Modern optimization techniques are a group of sophisticated mathematical and computational approaches used to identify the best answer to challenging situations. The field of research has expanded, and significant progress has been made in this domain. The primary focused optimization tuning techniques include: Self and Auto tuning [45], Robust and Optimal tuning [46], Genetic and Intelligent control strategies [47], Fuzzy and Adaptive tuning [48], and Fractional order PID control strategies [49]. Many different industries, including engineering, finance, machine learning, and data science, employ these techniques extensively [50].

The bio-inspired technique is the one that is most frequently used to tune PID controllers among modern optimization techniques. The behavior and adaptations of living things in nature serve as the basis for a class of optimization approaches known as "bio-inspired optimization techniques". These algorithms are created to solve complex problems by imitating natural processes like evolution, swarm intelligence, and neural networks. They work by searching for optimal solutions to problems, in their environments to achieve optimal outcomes [51-59]. Table III shows the comparison of various bio inspired tuning methods.

Table III. Various bio inspired tuning methods.

S. No.	Tuning Method	Inspiration	Features	Advantages	Disadvantages
1	Genetic Algorithm (GA) developed By John Holland and his collaborators (1960s & 1970s) [44]	Evolutionary theory of Darwin	Population-based search, selection, crossover and mutation	Globally optimal solution, suitable for multi-modal and multi problems	Slow convergence, need parameter tuning
2	Ant Colony Optimization (ACO) developed by Marco Dorigo in 1992 [45]	Ant behavior in seeking the shortest path	Design of probabilistic solutions and pheromone updates	Effective for discrete optimization problems and resistant to noise	Limited scalability, sensitivity to parameter adjustment
3	Particle Swarm Optimization (PSO) introduced by Kennedy & Eberhart (1995) [46]	Swarm behavior of fish and birds	Population-based search, velocity update, personal and global best positions	Fast convergence, easy implementation, suitable for continuous and discrete problems	Premature convergence, prone to stagnation
4	Differential Evolution (DE) Introduced by Storn in 1997 [47]	Genetic variation and recombinatio n	Population-based search, differential mutation, crossover	Suitable for high-dimensional and non-linear problems, simple implementation, and noise-resistant.	Limited exploration potential, sensitive to parameter tuning
5	Artificial Bee Colony (ABC) introduced by Derviş Karaboğa in 2005 [48]	Foraging behavior of honeybees	Employed, onlooker, and scout bees, food source exploitation	Simple to implement, quickly converges, and works for both continuous and discrete situations	Not suitable for complex problems, limited exploration ability
6	Firefly Algorithm (FA) developed by Xin-She Yang in 2008 [49]	Bioluminesce nce of fireflies	Attraction, brightness, and randomization phases, attractiveness update	Simple implementation, strong exploratory skills, and appropriate for continuing problems	Premature convergence prone, adjustment of parameters sensitive
7	Cuckoo Search (CS) developed in 2009 by Xin-She Yang and Suash Deb [49]	Brood parasitism of cuckoo birds	Levy flights, random walk, and egg-laying operations	Suitable for continuous optimization problems, good exploration ability	Sensitive to parameter tuning, prone to premature convergence
8	Bat Algorithm (BA) developed by Xin-She Yang in 2010 [49]	Echolocation of bats	Frequency and loudness tuning, velocity update, and random walk	Fast convergence, straightforward implementation, and suitability for continuous problems	A limited capacity for investigation and sensitivity to parameter tuning
9	Gray Wolf Optimization (GWO) put forward by Seyedali Mirjalili etc in 2014 [50]	Hunting behavior of grey wolves	Alpha, beta, delta, and omega wolves, search and update operations	Good exploration and exploitation skills, appropriate for ongoing issues	Limited scalability and parameter tuning sensitivity

The integer and fractional order PID controllers in this research are optimized using the particle swarm optimization method. The Particle Swarm Optimization (PSO) technique was introduced by Kennedy and Eberhart in 1995. This population-based approach is motivated by the swarming behaviour of fish and birds. The PSO is easy to implement which is suitable for both continuous and discrete problems. In this technique the optimal solution is achieved by the velocity update of particles' local and global best experience [60]. The following are the key actions that its algorithm takes. Figure 7 shows its steps in the form of flowchart

Step 1: Start
Step 2: Initialization
(Set up a population of particles in the search space with random positions and velocities.)
Step 3: Evaluation
(Based on the objective function, assess each particle's fitness.)
Step 4: Update Personal Best (P_{best})
(Each particle's personal best position and the associated fitness value, if the current position has a higher fitness than the best personal position.)
Step 5: Update Global Best (G_{best})
(Identify the particle in the population with the highest fitness value, then update the global best position accordingly.)
Step 6: Update Velocity and Position
(Using the current velocity, current position, personal best position, and global best position, adjust each particle's velocity and position.)
Step 7: Check stopping criterion
(Verify that the stopping criterion has been satisfied. If not, go back to step 3. Otherwise, terminate the algorithm.)
Step 8: Output
(The output of the algorithm is the best solution found during the optimization process.)
Step 9: End

The aforementioned actions are continued until a termination condition is met, such as when the required number of iterations is attained or a suitable solution is found. The PSO algorithm is iterative, which means that it improves the solution over a number of iterations while letting the particles explore the search space for the best answer.

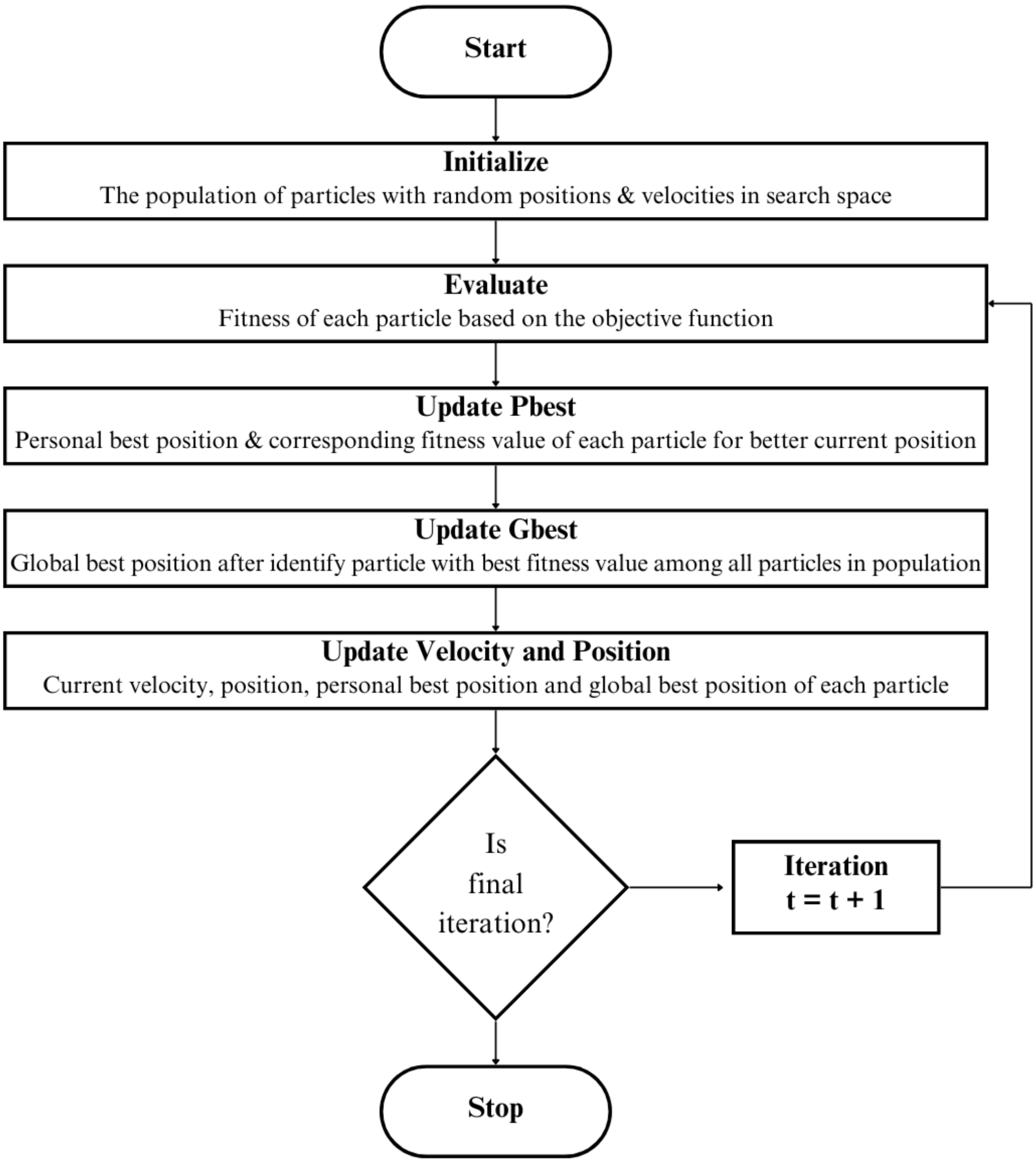


Figure 7. Flowchart of PSO technique.

III. Results and Discussion

To illustrate the proposed system, let us simulate the block diagram of the cardiac pacemaker with the controller, as shown in Figure 4 in MATLAB/Simulink. Before proceeding with all the necessary control analyses, the evaluation of optimal parameters of the integer-order PID controller gain (K_p, T_i, T_d) are required. It consists of the series connection of open-loop gain of the controller, pacemaker and heart respectively, which are arranged with unity feedback in a closed-loop manner.

In this work, the Ziegler Nichols method is applicable to evaluate the critical control parameters for the integer-order PID controller. After that various Ziegler Nichols optimization techniques and T-L optimization technique is applied to find the corresponding integer-order control parameters to apply to the controller to obtain desire response. The Figure 8 shows the Simulink model of the cardiac pacemaker without any controller with its step response. This simulated model is existing cardiac pacemaker system which is without any controller.

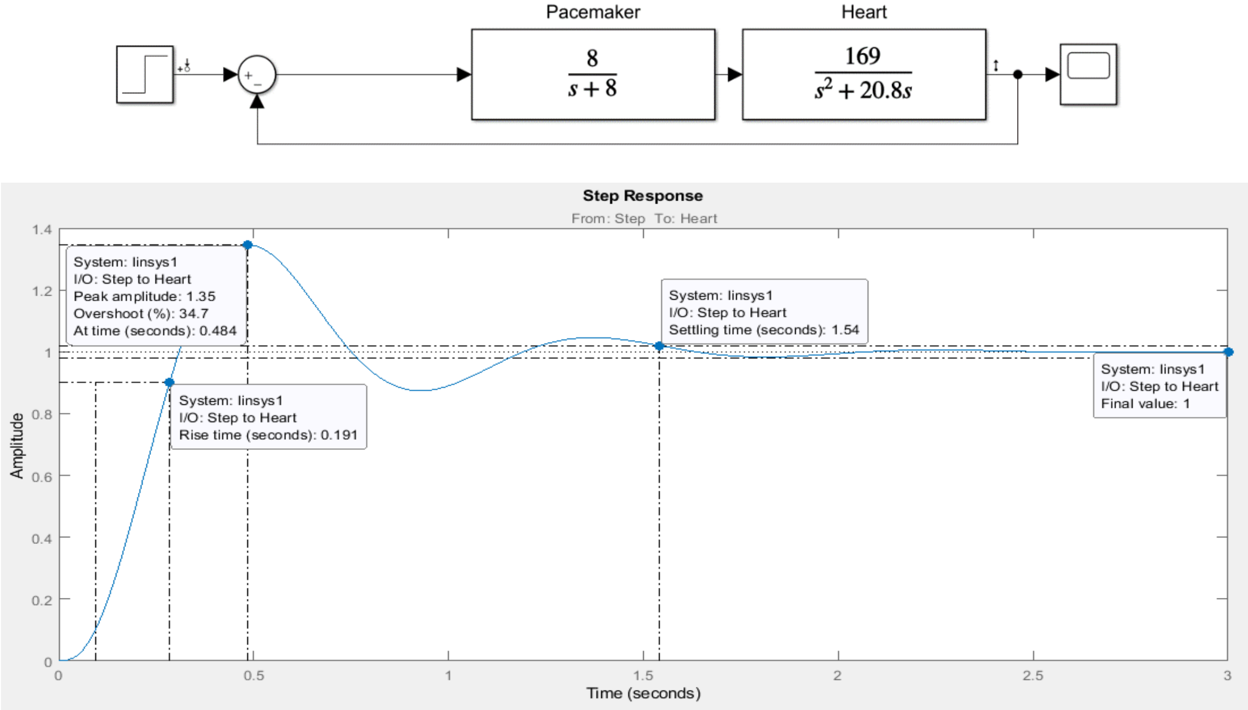


Figure 8. Simulink model of the cardiac pacemaker without any controller and its step response

Now, the Figure 9 shows the Simulink model of the cardiac pacemaker arranged with integer order PID controller optimized using various conventional tuning methods such as Ziegler Nichols and its modification with overshoot and no overshoot conditions and with T-L technique. The Figure 10, Figure 11, Figure 12, and Figure 13 shows the step response for all the models simulated on MATLAB as shown in Figure 9.

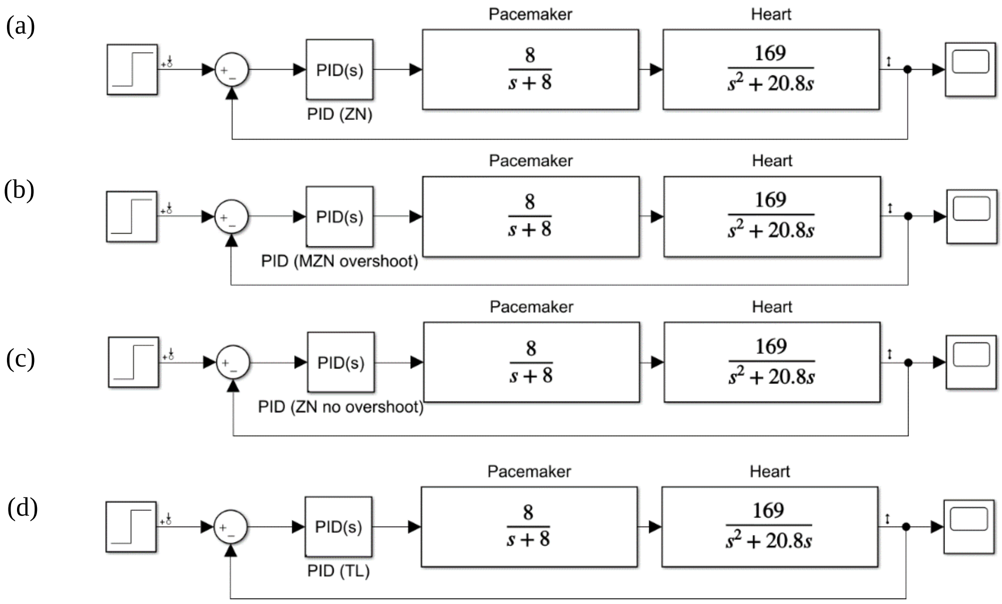


Figure 9. Simulink model of the cardiac pacemaker with PID controller tuned by (a) ZN, (b) MZN (overshoot), (c) MZN (no overshoot) and (d) TL methods.

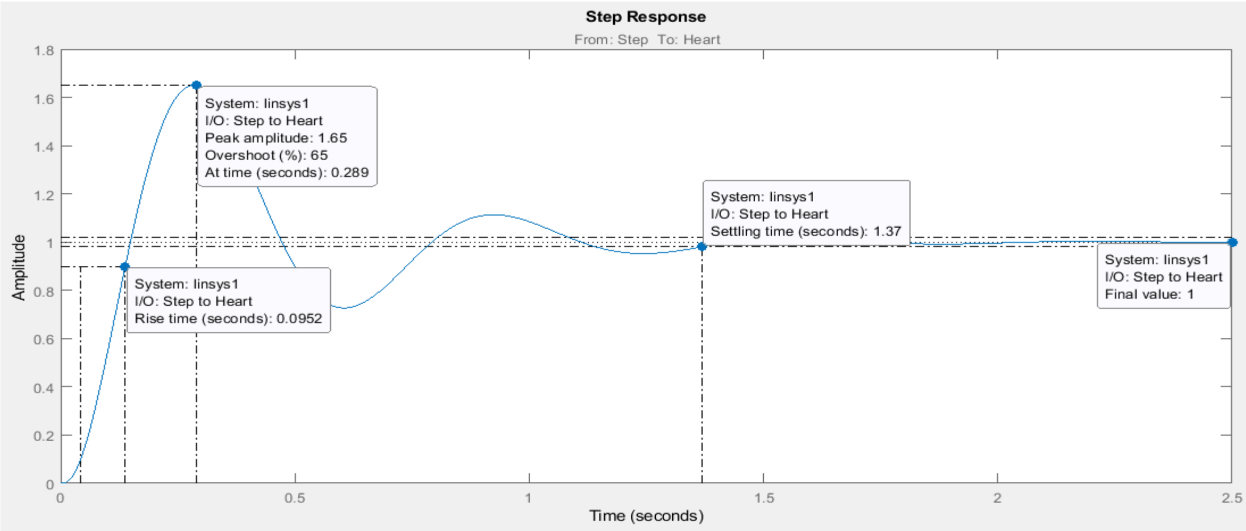


Figure 10. Step response of the cardiac pacemaker system with PID controller tuned by ZN tuning method.

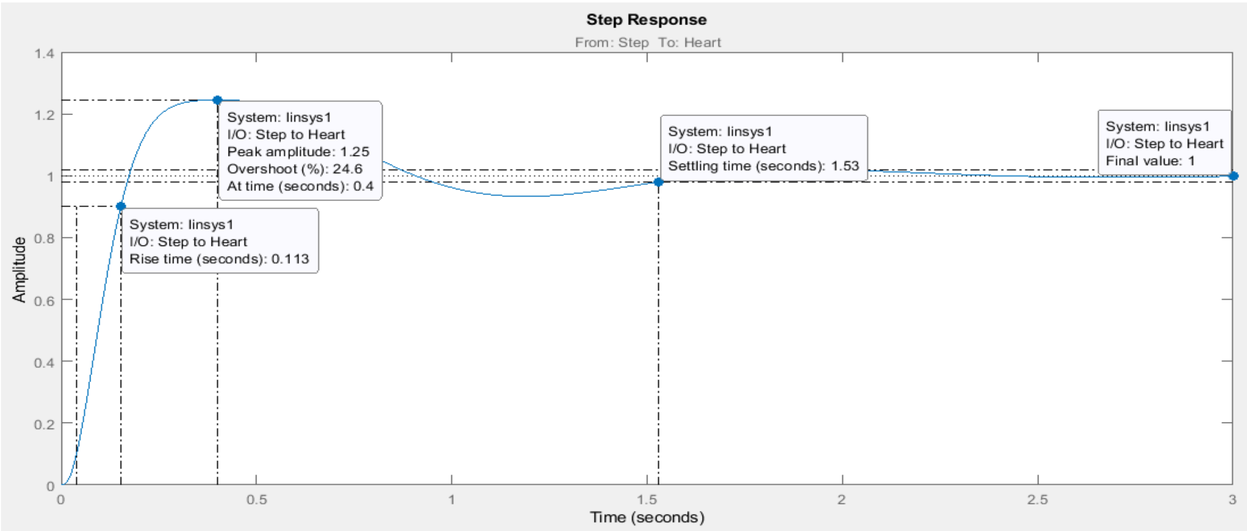


Figure 11. Step response of the cardiac pacemaker system with PID controller tuned by MZN (overshoot) tuning method.

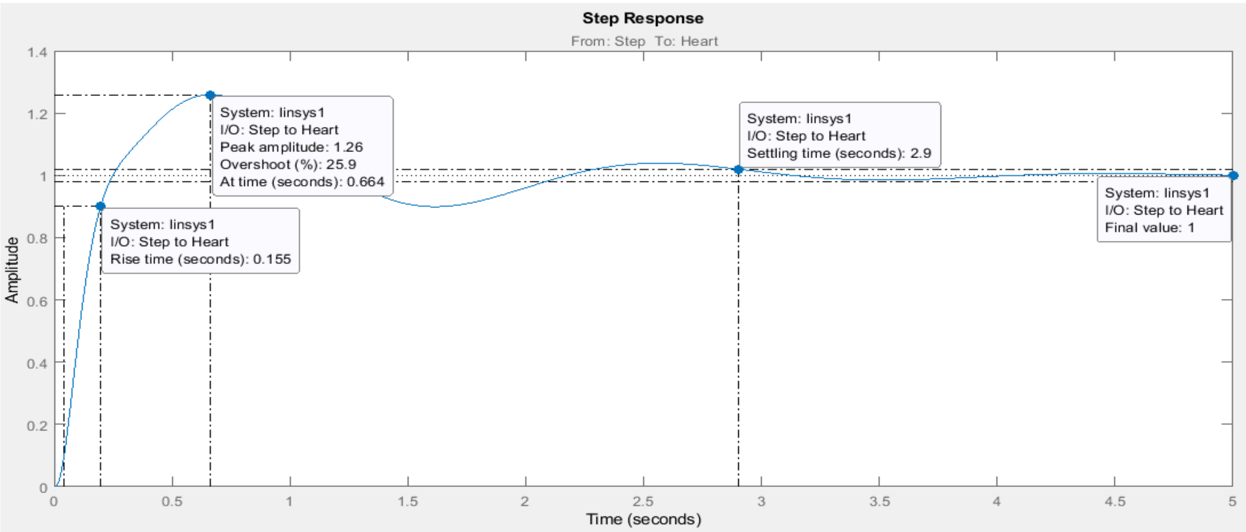


Figure12. Step response of the cardiac pacemaker system with PID controller tuned by MZN (no overshoot) tuning method.

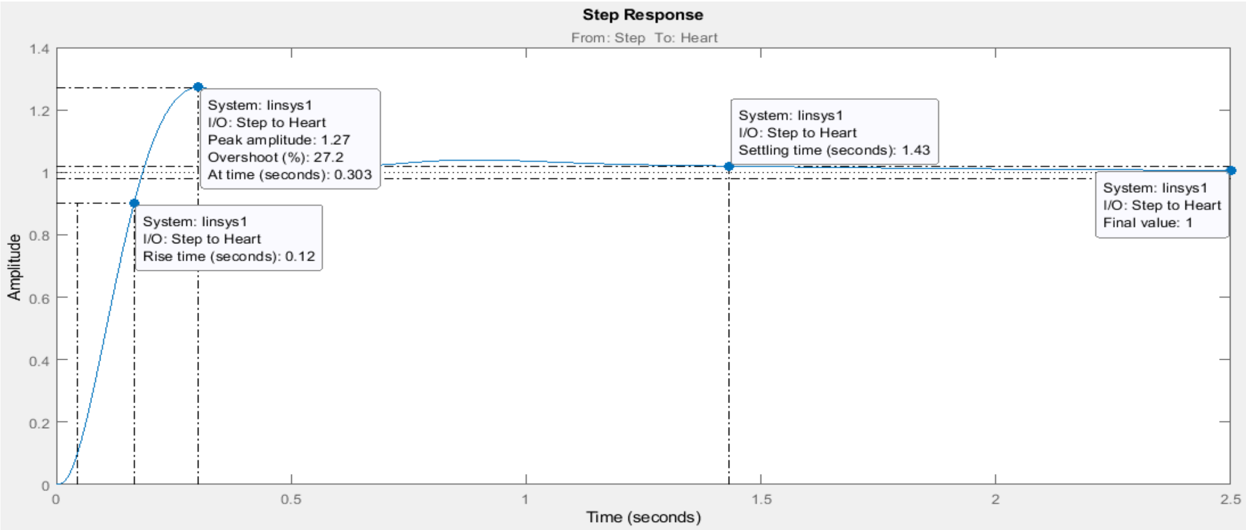


Figure 13. Step response of the cardiac pacemaker system with PID controller tuned by TL tuning method.

To observe the reaction of the cardiac pacemaker system, the integer and fractional order PID controllers are subjected to modern optimization using the particle swarm optimization technique after performing various conventional tuning on the integer order PID controller. The Figure 14 shows the particle swarm optimization-tuned close-loop model of the cardiac pacemaker system with integer and fractional order PID controller.

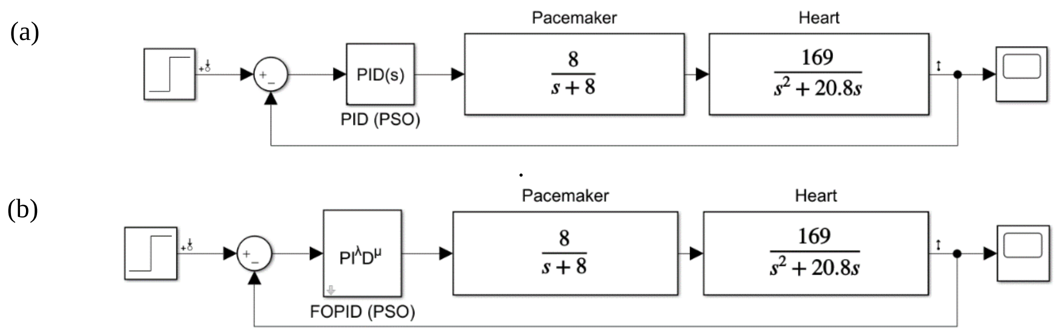


Figure 14. Simulink model of the cardiac pacemaker with (a) Integer order and (b) Fractional order PID controller tuned by particle swarm optimization (PSO) method.

The Figure 15 and Figure 16 shows the step response of the cardiac pacemaker system with integer and fractional order PID controller optimized using the particle swarm optimization (PSO) method. It is clear from these responses that the system responds better than the controller tuned using different conventional tuning techniques.

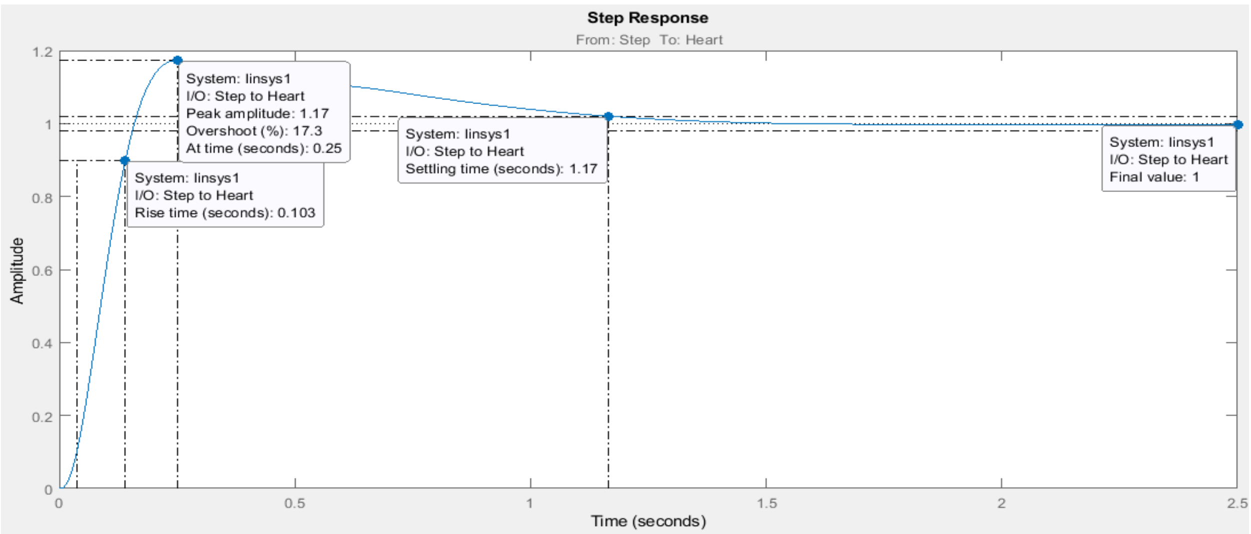


Figure 15. Step response of the cardiac pacemaker system with integer order PID controller tuned by particle swarm optimization (PSO) method.

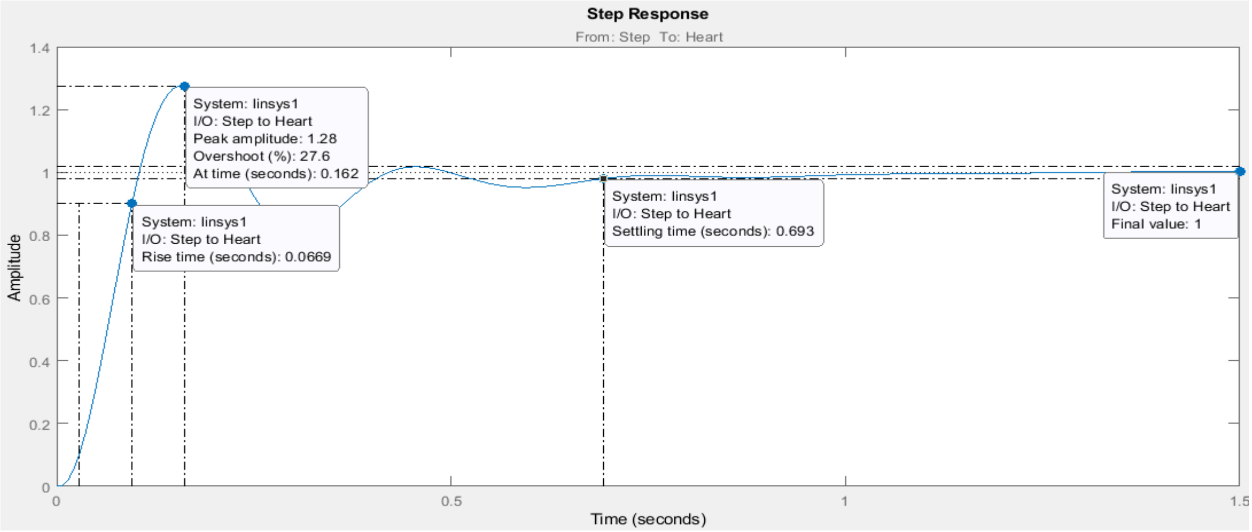


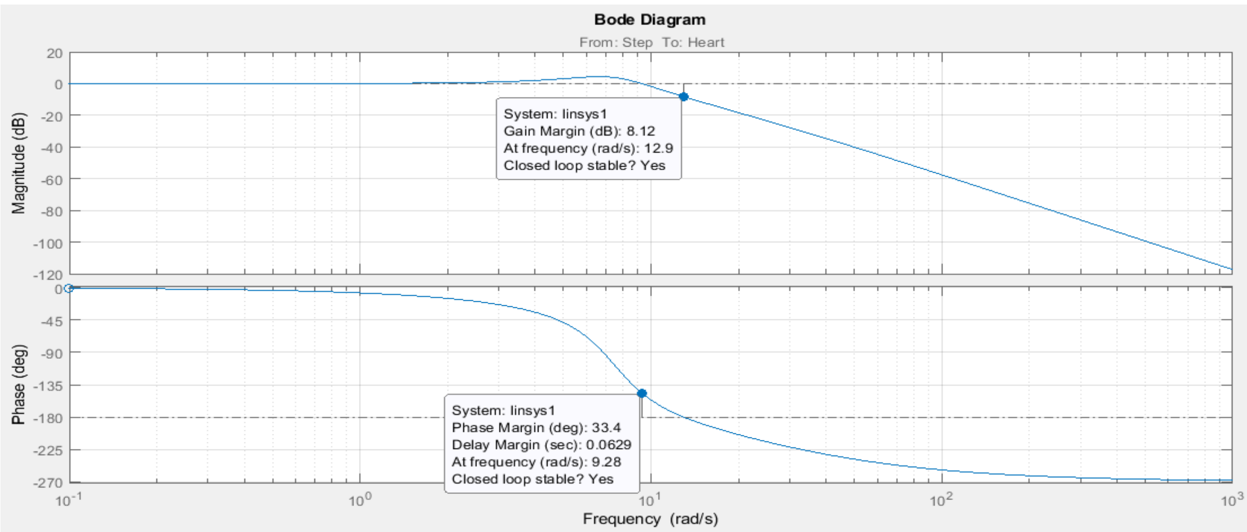
Figure 16. Step response of the cardiac pacemaker system with fractional order PID controller tuned by particle swarm optimization (PSO) method.

Table IV provides a thorough comparison of the parameters determined by system analysis following the implementation of optimized integer and fractional order PID controllers.

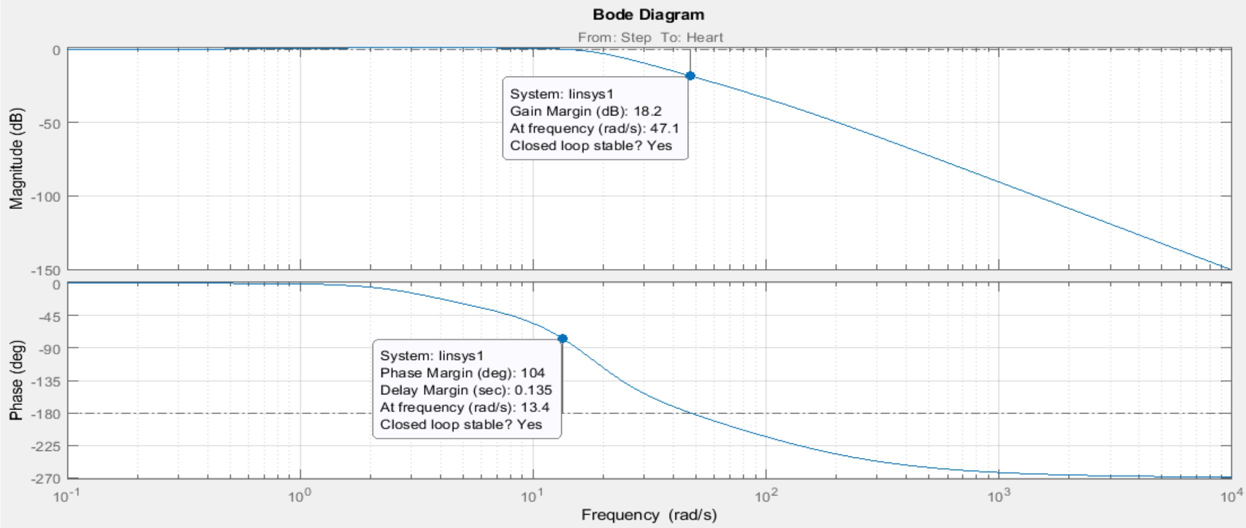
Table IV. Comparative parameters.

S. No.	System	Parameters		
		Rise Time	Settling Time	Overshoot
1	Without PID (Existing System)	0.191s	1.54s	34.7%
2	PID (ZN)	0.0952s	1.37s	65%
3	PID (MZN; No Overshoot)	0.155s	2.9s	25.9%
4	PID (MZN; Overshoot)	0.113s	1.53s	24.6%
5	PID (TL)	0.12s	1.43s	27.2%
6	Integer order PID (PSO)	0.103s	1.17s	17.3%
7	Fractional order PID (PSO)	0.0669	0.693	27.6%

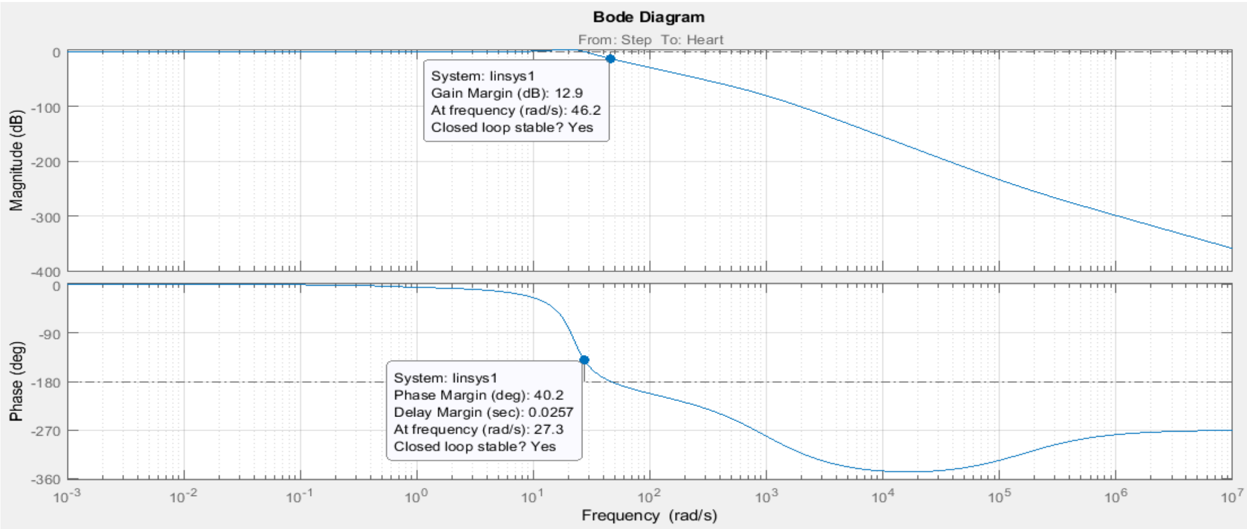
To check the stability of the system, the Bode plot for all the proposed controllers for cardiac pacemaker system is also obtained. The Figure 17 shows the bode plot of the existing system and particle swarm optimized integer and fractional order controller. Refer Table V for associated values.



(a)



(b)



(c)

Figure 17. Bode plot for cardiac pacemaker system. (a) Existing System (without PID), (b) Integer order PID (PSO) and (c) Fractional order PID (PSO).

Table V. Values of gain margin and phase margin obtained by Bode plot.

S. No.	System	Parameters	
		Gain Margin	**Phase Margin**
1	Without PID (Existing System)	8.12 dB	33.4˚
2	Integer order PID (PSO)	18.2 dB	104˚
3	Fractional order PID (PSO)	12.9 dB	40.2˚

Observe all responses now to draw the conclusion that the incorporation of an optimized integer and fractional order PID controller enhances the cardiac pacemaker system's response but all the optimization techniques have their limitations. These limitations can be removed by the advancement of the system.

IV. Conclusion

For a cardiac pacemaker to control the heart rate of a cardiac patient, a reliable integer and fractional order PID controller-based system is designed. Initially, it has been concluded by simulating and performing the control analysis to the existing system; the system without any controller that there is a wide scope of the robust controllers. After that applying the optimized integer order controller using Ziegler Nichols and T-L method to the existing cardiac pacemaker system it has been observed that the system is generating improved control characteristics such as settling time, overshoot and rise time.

In this work, the robust cardiac pacemaker system is designed using an integer and fractional order controller for regulating the heart rate of a cardiac patient. At present, the introduction of fractional order controllers to various systems has provided robustness by improving control characteristics. The fractional-order controllers have two additional parameters compared to integer-order controllers, adding an additional degree of controllability. Also, there is the availability of a large variety of modern optimization techniques which can be applied to both integer and fractional order controllers and it is observed in various literatures that they provide improved characteristics than any other optimization techniques. In this research, the particle swarm optimization technique demonstrated improved control parameter results. For the benefit of improving human health, the suggested technique of approach can also be used with different kinds of bio-medical applications. The cardiac pacemaker system with an integer and fractional order controller is more stable, as shown by the Bode plots of the existing system and the proposed system, as the system with an optimized controller has a larger gain margin and phase margin.

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