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Intelligent Heart Rate Controller for Cardiac Pacemaker

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ABSTRACT

In the recent years improvement in the patient's quality-of-life has become a focal point in the development of new and optimized techniques for electro stimulation of the heart. In an effort to make such improvements the present work describes the design of a control system for regulating the Heart Rate (HR) for pacemaker in an efficient way. The overall control system to be developed, in this work is considered to be composed of cardiovascular system duly energized by an intelligent pacemaker system as operated in a closed loop manner with unity negative gain in the feedback path. A conventional controller based on Proportional, Integral and Derivative (PID) is designed with the help of Zeigler-Nichols, Tyreus-Luyben and Relay tunings methods. In addition, HR controller is also designed using fuzzy controller to improve response parameters. By competitive study of results of fuzzy and PID controller it is found that the overall response of fuzzy logic based controller is better than the conventional PID controller.

General Terms

Intelligent Controller, Cardiac Pacemaker.

Keywords

Pacemaker, Fuzzy Logic, PID, Heart Rate Controller, Heart Rate, Cardiovascular System.

1. INTRODUCTION

Diagnosis of human heart abnormalities is very important for improving the patient's quality of life. By measuring the changes in the pattern of heart electrical properties, the patients can be saved from serious health problems. Over the past decade, there have been significant changes in evaluation of patients with chest pain and suspected myocardial injury. The most commonly employed diagnostic method currently used (recommended by WHO) in the recognition of myocardial ischemia and infarction is Electrocardiography (ECG). Heart rate (HR) can be measured by calculating R-R interval of ECG. Normally rhythm of heart is synchronized by natural pacemaker of heart i.e. SA node. If there is any problem in conduction system of heart, a pacemaker is used. It applies an electrical impulse once it detects any ambiguity in the HR which may occur due to changes in electrical activity of the heart.

In the recent years several researchers have developed the controller system to bring working of heart to normal condition. S. C. Biswas *et al.* proposed a mathematical model of cardiovascular system using transfer function method [1]. Inbar *et al.* designed a closed loop pacemaker by using PI (proportional and integral) controller for regulating the mixing venous oxygen saturation level [2]. The performance of controller was demonstrated through its computer simulation. Sugiura *et al.* used a fuzzy approach to control HR using an artificial cardiac pacemaker regulated by respiratory rate and temperature. It was concluded from the results that the fuzzy method is well suited for the application [3]. Shin *et al.* proposed a neuro-fuzzy controller to study the rate adaptive pacemaker by motion and respiration. It is observed that the neuro-fuzzy inferred HR is more accurate than the one using normal fuzzy table look-up method [4]. Wojtasik, *et al.* also designed a fuzzy logic controller for rate-adaptive heart pacemaker [5]. The several authors have designed a family of fuzzy logic controllers for rate-adaptive cardiac pacemakers. The implemented algorithm offers good adaptation to the change in HR according to physiological needs of the patient and easy personalization. Several other researchers have also reported different algorithms for cardiac pacing [6-9].

Recently, Neogi *et al.* worked on simulation aspect of an artificial pacemaker. The authors have designed and analysed a control system for regulating the HR using pacemaker in an efficient way. The design emphasizes on the optimality in operation which is determined by the performance index of the total process. Optimality is attained by using a compensator along with the cascade arrangement of the cardio vascular system driven by the concerned pacemaker. It is concluded from the results that the developed system is controllable and observable [10].

In present work simulation aspect of HR controller is considered for designing a cardiac pacemaker. The HR controller for cardiac pacemaker is designed using two types of controllers i.e. PID and fuzzy controller. The simulation of the system is done using MATLAB software.

2. PACEMAKER

An artificial pacemaker is a medical device used to stimulate the heart muscles in case of any problem in natural conduction system of heart to regulate the rhythm of heart. Broadly pacemaker has two functional units: first is "sensing circuit" by which it senses the patient's HR and second is "output circuit" through which it sends out electrical signals to heart muscles. This electrical signal is used to control the HR of the patient. If patient HR becomes too slow (bradycardia), the pacemaker senses the abnormal signal and start sending a regular excitation signals to heart muscles which forces the heart to contract at a rate fast enough to maintain the patient's heart rhythm normal.

3. HEART RATE CONTROLLER

The cardiovascular system is considered to be a closed loop system with filter and controller with unity negative feedback. Figure 1 shows a simplified model of a closed loop control system for regulating the HR of a patient in an efficient way.

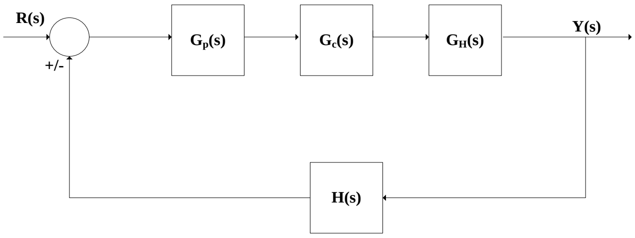


Figure 1: Block diagram of Heart Rate Controller for Cardiac Pacemaker

$G_P(s)$ = Transfer function of Pacemaker
$G_C(s)$ = Transfer function of controller
$G_H(s)$ = Transfer function of Heart
$R(s)$ = Actual heart rate
$H(s) = 1$
$Y(s)$ = Desired heart rate

3.1 PID Controller

The proportional–integral–derivative (PID) controller is a conventional controller which takes the error signal as an input. The error signal is basically difference between measured process variable and desired set point. The Controller adjusts the process control inputs by minimizing the error signal. The value of PID parameters must be tuned according to the nature of the system [11].

The PID controller design involves three separate parameters; proportional, integral and derivative gain. The proportional gain reaction based on the current value of error signal, the integral gain reaction based on the sum of recent errors, and the derivative gain reaction based on the rate of change of error signal. The weighted sum of reactions of these three parameters is used to adjust the HR. The overall response of control system composed of PID controller is given by (1). C(s) is transfer function of controller.

$$C(s) = K_p + \frac{K_i}{S} + K_d s$$

$$= K_P\left(1 + \frac{1}{T_i s} + T_d s\right) \ldots\ldots (1)$$

Where K_p = Proportional Gain

K_i = Integral Gain, Ti =Integral Time constant $=K_p/K_i$

K_d =Derivative gain, T_d = Derivative Time constant

To obtain the initial values of three parameters K_p , K_i K_d tuning of PID is required. By tuning the three constants (K_p, T_i, T_d) of PID controller control action can be provided according to specific process requirements. The response of the controller can be evaluated in terms of transient and steady state performance parameters of the output namely: Overshoot, Rise time, Settling time, Oscillations and Steady state error.

The methods used for tuning of PID parameters are as follows:

3.1.1 The Ziegler–Nichols tuning method

This is a heuristic method of tuning a PID controller. It was developed by John G. Ziegler and Nathaniel B. Nichols. The process of tuning the parameters is as follows:

a) Put the values of $T_i=\infty$ and $T_d=0$

b) Now increase the value of K_p from 0 to critical value K_{cr}

c) The values of K_p at which output exhibits sustained oscillations is critical gain K_{cr}

d) Obtain the values of period P_{cr} corresponding to critical gain K_{cr}

Put the values of K_{cr} and P_{cr} in the formula shown in table1 to obtain the values of the parameters K_p, T_i and T_d [12].

Table 1: Ziegler –Nichols rule base on critical gain K_{cr} and critical period P_{cr} of a plant

Type of controller	K_c	T_i	T_d
P	$0.5K_{cr}$	∞	0
PI	$0.45K_{cr}$	$\frac{1}{1.2}P_{cr}$	0
PID	$0.6K_{cr}$	$0.5P_{cr}$	$0.125P_{cr}$

To improve the robustness of system Tyreus- Luyben method of PID tuning is used.

3.1.2 Tyreus- Luyben method

To reduce the oscillatory effects and to improve the robustness of the system Tyreus- Luyben (TLC) method of tuning is used to obtain the parameters of PID and PI controller [13]. As explained above, the values of K_{cr} and P_{cr} are used for tuning of PID controller using Table 2.

Table 2: Tyreus - Luyben method

Tyreus – Luyben	K_c	T_i	T_d
PI control	$K_{cr}/3.2$	$2.2\,P_{cr}$	-
PID control	$K_{cr}/2.2$	$2.2\,P_{cr}$	$P_{cr}/6.3$

3.1.3 Relay method

To avoid the trial and error Relay method is used. This method provides a simple way to tune PID controller. It also reduces the possibility of operating the system close to the stability limit [14].The procedure is explained as follows:

1. Relay of amplitude d is placed in feedback of system
2. Then system starts oscillate with output amplitude a and time period P at the critical frequency.
3. The critical time period is equal to the observed period P_{cr} = P and critical gain is inversely proportional to the

Observed amplitude, $K_{cr} = 4d/\pi a$

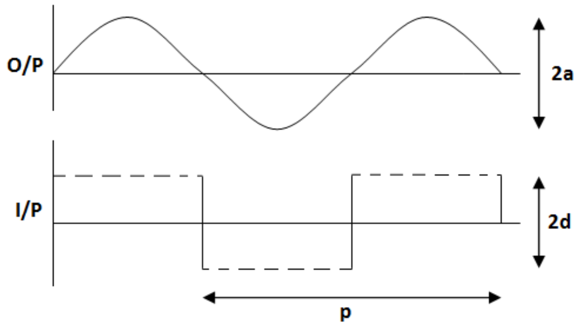


Figure 2: A plant oscillating under relay feedback with the PID regulator temporarily disabled

The values of K_{cr} and P_{cr} obtained above are used for tuning of PID controller according to table 1.

3.1.4 Fuzzy Logic Based Controller System

The fuzzy logic-based controller (FLC) was first implemented by Mamdani and Assilian based on the fuzzy logic system generalized from fuzzy set theory introduced by Zadeh [15]. The block diagram of a FLC shown in Figure 3 is consisting of the following main units:

a) Fuzzification: The observed data is in crisp form so fuzzification at input stage is required to convert the data in fuzzy form for manipulation of data using fuzzy theory.

b) Fuzzy inference engine: Fuzzy inference engine employs the fuzzy decision-making based on knowledge base to simulate control actions

c) Knowledge base: The knowledge base of the FLC consists of database and rule base. The rule base provides the required information for proper fuzzification and defuzzification

d) Defuzzification: Finally, the defuzzification is used to convert the output of FLC into the crisp data for real world applications.

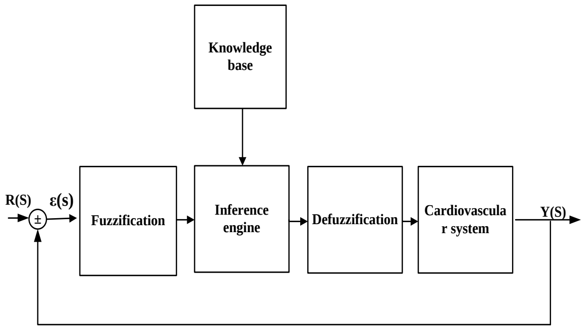


Figure 3: Block diagram of fuzzy controller

The input error ε(s) is first fuzzified by defining the range in which it gets varied and the membership functions for this range [16]. In Figure 3, R(s) is reference input, ε(s) is error signal and Y(s) is output of the process

4. SIMULATION OF PACEMAKER

The model of pacemaker is simulated as shown in Figure 4 and Figure 5. The values of parameters are: R(s) = reference heart rate; Y(s) = desired heart rate, $G_P(s) = 8/(s+8)$ is low pass filter transfer function, allowing various excitations of lower frequency and rejecting higher frequencies, as evolved in normal metabolic process for the regular function of a cardiovascular system of a living being[17]. Consideration is focused on the fact that the cardiovascular system can be modelled as an under damped second order system having suitable parametric values of the damping factor and the natural frequency, so that the heart performs its normal function appropriately. Hence, the transfer function $G_H(s)$ of the heart is chosen as given by the following expression [18] $G_H(s) = 169/(s^2 + 20.8s)$. The controller designed in the present work is proportional plus derivative plus integral controller (PID), its transfer function is shown in (1). Normal adults have HR around 75 Beats/min. In present work three cases are considered when HR=65 (for old age person), HR=75 (Normal adult), HR=85 (for young active person). During daily activities HR may increase/decrease in order to supply oxygen according to body needs. Figure 4 and Figure 5 show the cardiovascular system and pacemaker (controller plus low pass filter) in closed loop with unity feedback. The PID and fuzzy controllers are used for regulating the HR separately with low pass filter. Three different methods: Zeigler-Nichols, Tyreus-Luyben and Relay techniques are used for tuning of PID controller.

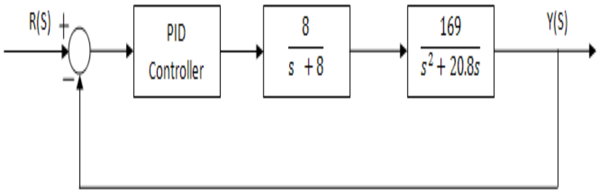


Figure 4: Closed loop diagram of cardiovascular system with PID controller

Block diagram of a cardiovascular system with fuzzy controller in closed loop is shown in Figure 5. The two inputs defined for the controller are: error E(s) and rate of change of error sE(s). Both the inputs are based on rule base of 9 membership functions. These two inputs are first fuzzified by defining the range in which they get varied and defining the membership functions accordingly for this range [18] [19]. In Figure 5 two scaling K_1 and K_2 are used for selection of the range of error E(s) and change in error sE(s). E(s) is the difference between measured process variable and desired reference point. E'(s) is fuzzified input to the fuzzy controller.

$$E'(s) = E(s)K_1 + E(s)K_2 \text{ Where } K_1 > 0,\ K_2 > 0 \ldots \quad (2)$$

K_3 is scaling factor for defuzzification of output of fuzzy controller.

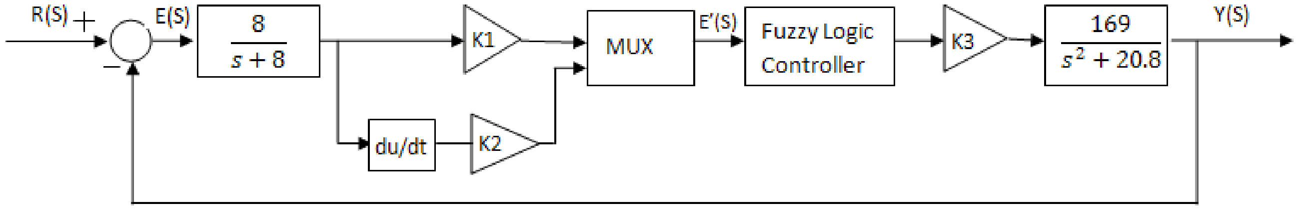


Figure 5: Close loop diagram of cardio vascular system using Fuzzy controller with unity negative feedback

Table 3: Rule base for fuzzy controller

Controller output ↘		**Rate of change of Error(de/dt)**								
		VVVNL	VVNL	VNL	NL	ZERO	PL	VPL	VVPL	VVVPL
Error (e)	VVVNL	VVVNL	VVNL	VNL	VNL	VNL	NL	VNL	PL	PL
	VVNL	VVVNL	VVNL	VNL	VNL	VNL	VNL	PL	PL	PL
	VVNL	VVNL	VVNL	VVNL	VNL	VNL	NL	NL	PL	VPL
	NL	VVNL	VNL	VNL	NL	NL	NL	PL	PL	VPL
	ZERO	VNL	VNL	NL	NL	ZERO	PL	VPL	VPL	VPL
	PL	VNL	NL	NL	PL	PL	VPL	VPL	VVPL	VVPL
	VPL	NL	NL	PL	PL	VPL	VPL	VPL	VVPL	VVPL
	VVPL	NL	PL	PL	VPL	VPL	VPL	VVPL	VVPL	VVVPL
	VVVPL	PL	PL	VPL	VPL	VPL	VVPL	VVPL	VVVPL	VVVPL

A set of 'if-then' rules is made so that any combination of input rules results in an appropriate output value. For a fuzzy logic controller with two inputs E(s) and, sE(s), E(S) input having 9 term sets {VVVNL, VVNL, VNL, NL, ZERO, PL, VPL, VVPL, VVVPL}, sE(s) input having 9 term sets {VVVNL, VVNL, VNL, NL, ZERO, PL, VPL, VVPL, VVVPL}, the total number of rules will be equal to 9 × 9 = 81. A representation rule-set for fuzzy controller is shown in table 3.

5. RESULTS AND DISCUSSION

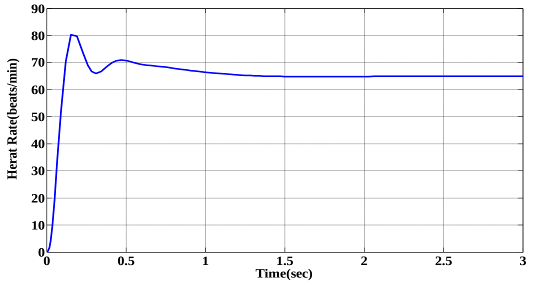
The results obtained with the help of PID controller tuned with different techniques are as follows:

5.1 Zeigler- Nichols tuned PID controller

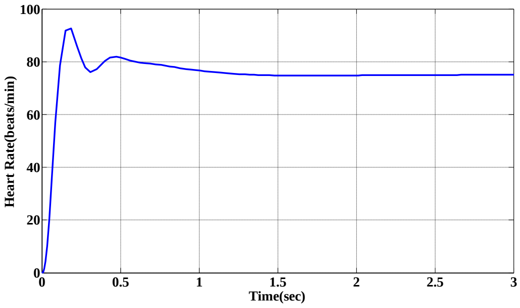
Initially PID controller is tuned with the help of Ziegler-Nichols method. The response of process using PID controller is depicted in Table 4 in terms of different performance parameters. Three different cases of HR are taken into Consideration separately as reference inputs. The performance parameter values for HR=65, HR=75 and HR=85 are shown in Figure 6 (a-c) respectively. It is observed from Figure 6 (a-c) that overshoot and settling time are very high by using PID controller tuned with Ziegler-Nichols method. The oscillations are also observed in the response of the process. Therefore to check the feasibility of getting improved performance Tyreus- Luyben method is used for tuning of PID controller.

Table 4: Response parameter of PID controller tuned with

HR	**Rise Time**	**Settling Time**	**Maximum % Overshoot**
65	0.0714	1.0204	23.5488
75	0.0714	1.0195	23.4504
85	0.0711	1.0198	24.0782



(a)



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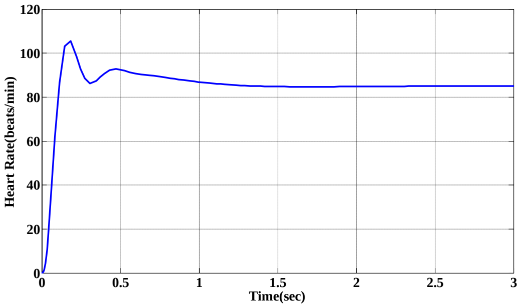


(c)

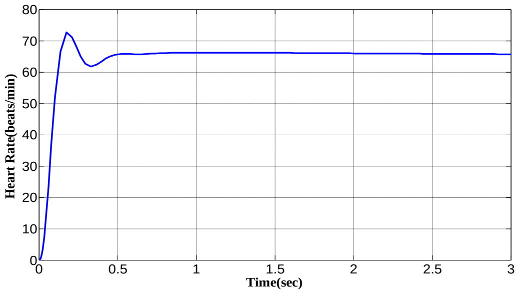
Figure 6: Response of the PID controller tuned with Zeigler- Nichols method for (a) HR=65 (b) HR=75 (c) HR =85

5.2 Tyreus- Luyben tuned PID controller

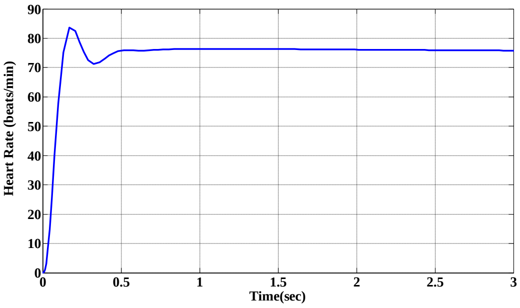
The response of PID controller tuned with Tyreus - Luyben method for different cases are shown in Figure 7 (a-c) respectively. The changes in performance parameters of PID controller are depicted in Table 5. It is observed from Figure 7(a-c) that the settling time and overshoot are significantly less as compared to the response of PID controller tuned with Zeigler-Nichols method. Still the response need to be improved and to check the feasibility of getting desired results, one more method i.e. relay technique is used which is explained in next section.

Table 5: PID controller tuned with Tyreus -Luyben method

HR	Rise Time	Settling Time	Maximum % Overshoot
65	0.0860	0.4098	11.7242
75	0.0856	0.4098	11.4107
85	0.0853	0.4095	10.9494



(a)



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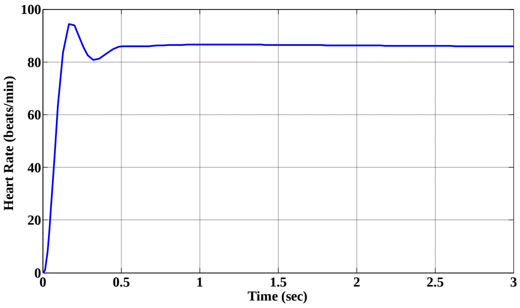


(c)

Figure 7: Response of the PID controller tuned with Tyreus - Luyben method for (a) HR=65 (b) HR=75 (c) HR =85

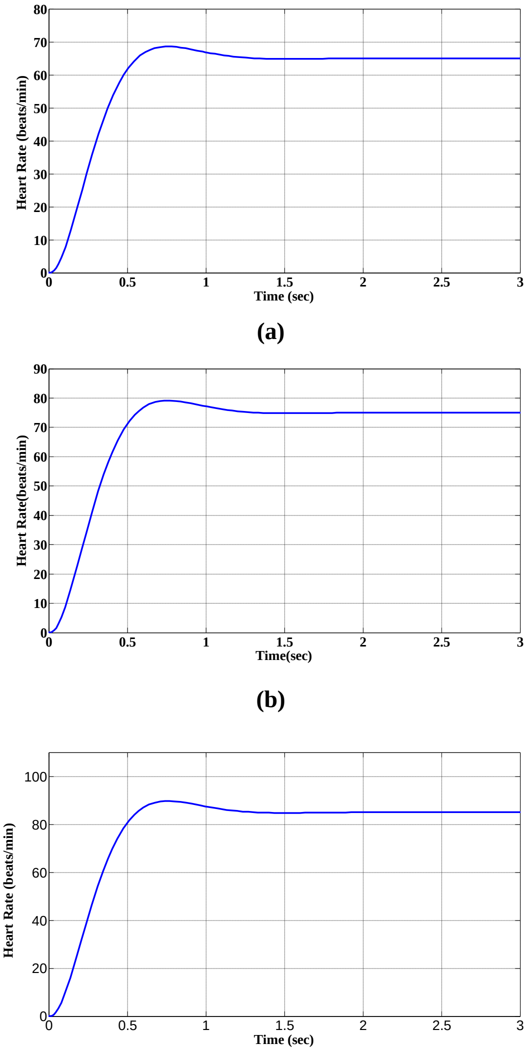
5.3 Relay tuned PID controller

The response of PID controller tuned with Relay method for different cases are shown in Figure 8 (a-c) respectively. The performance parameters of PID controller are depicted in Table 6. It is observed from Figure 8 (a-c) that overshoot is significantly less as compared to the response of PID controller tuned with Zeigler-Nichols and Tyreus-Luyben method. Settling time and rise time of PID controller tuned with relay method is higher than Tyreus -Luyben tuning method. The overshoot values of PID controller tuned with relay method are significantly less as compared to the previous two tuning methods. Therefore to improve overall performance of PID controller a robust and adaptive technique is needed.

Table 6: PID controller tuned with Relay method

HR	Rise Time	Settling Time	Maximum % Overshoot
65	0.3621	1.0617	5.4812
75	0.3626	1.0616	5.4877
85	0.3625	1.0617	5.4936

Generally FLC systems give better system response. Some of the studies using fuzzy set theory in engineering applications have proved that, nonlinear fuzzy controller gives better response than conventional controller and local stability can also be achieved using FLC. Therefore to improve the performance of the PID controller fuzzy based control system is designed.



(a)

(b)

(c)

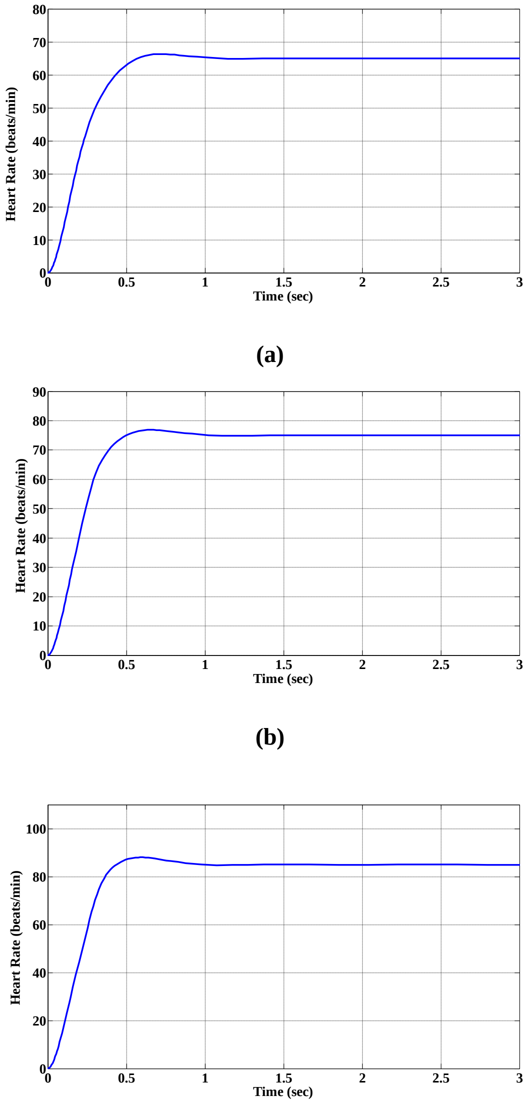
Figure 8 : Response of the PID controller tuned with Relay method for (a) HR=65 (b) HR=75 (c) HR =85

5.4 Fuzzy logic based controller system

The responses of fuzzy controller for different cases of HR are shown in Figure 9 (a-c) respectively. The performance parameters of fuzzy controller are depicted in Table 7. It is observed from Figure 9 (a-c) that overshoot is very less as compared to response of PID controller tuned with different methods. It is also observed from Figure 9(a-c) and Table 7 that the overshoots are combatively less as compared to PID tuned with different methods and overall performance of fuzzy controller is satisfactory.

Table 7: Results obtained using Fuzzy controller

HR	Rise Time	Settling Time	Maximum % Overshoot
65	0.3442	0.7563	2.0938
75	0.2917	0.7477	2.5117
85	0.2726	0.7631	3.5856



(a)

(b)

(c)

Figure 9: Response of the PID controller tuned with fuzzy controller for (a) HR=65 (b) HR=75 (c) HR =85

5.5 Comparison of PID and fuzzy controller results

The result obtained by PID controllers tuned with different methods and fuzzy controller is depicted in Table 8, 9 and 10 for different cases of HR. It is observed form Figure 10-12 and Tables 8-10 that rise time of fuzzy controller is less as compared to response of PID controller tuned with relay method and it is more as compared to the response of PID controller tuned with Zeigler-Nichols and Tyreus-Luyben method. It is observed in Figure 10-12 and also in Tables 8-10 that the settling time of fuzzy controller significantly lesser than the response of PID controller tuned with Zeigler-Nichols and Relay method but surprisingly it showed higher values as compared to the response of PID controller tuned with Tyreus-Luyben method. The overshoot is least in case of fuzzy controller as compared with PID tuned with different tuning methods. The overall performance of fuzzy controller is more promising than that of the PID controller performance.

Table 8: Comparison of result obtained by PID tuned with different techniques and fuzzy controller when HR=65

Method	Rise Time	Settling Time	Maximum % Overshoot
Fuzzy	0.3442	0.7563	2.0938
Zeigler - Nichols	0.0714	1.0204	23.5488
Tyreus - Luyben	0.0860	0.4098	11.7242
Relay	0.3621	1.0617	5.4812

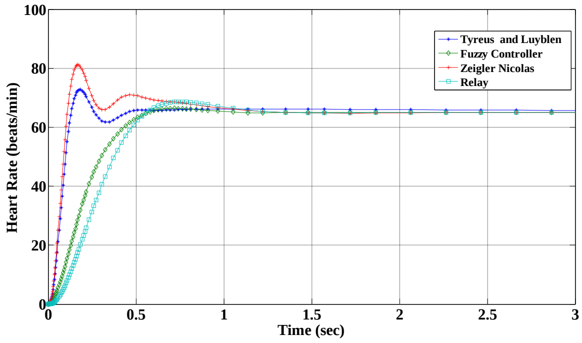


Figure10: Comparison of result obtained by PID tuned with different techniques and fuzzy controller when HR=65

Table 9: Comparison of result obtained by PID tuned with different techniques and fuzzy controller when HR=75

Method	Rise Time	Settling Time	Maximum % Overshoot
Fuzzy	0.2917	0.7477	2.5117
Zeigler - Nichols	0.0714	1.0195	23.4504
Tyreus - Luyben	0.0856	0.4098	11.4107
Relay	0.3626	1.0616	5.4877

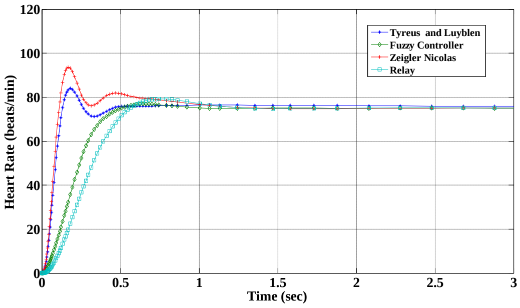


Figure 11: Comparison of result obtained by PID tuned with different techniques and fuzzy controller when HR=75

Table 10: Comparison of result obtained by PID tuned with different techniques and fuzzy controller when HR=85

Method	Rise Time	Settling Time	Maximum % Overshoot
Fuzzy	0.2726	0.7631	3.5856
Zeigler - Nichols	0.0711	1.0198	24.0782
Tyreus - Luyben	0.0853	0.4095	10.9494
Relay	0.3625	1.0617	5.4936

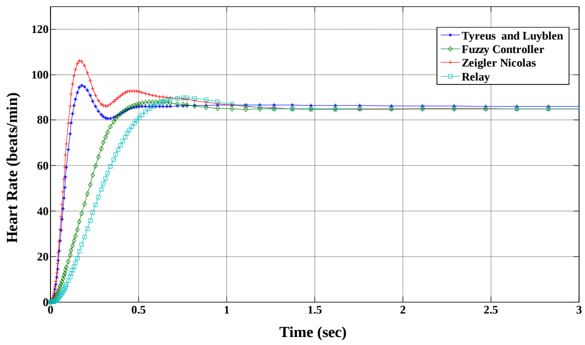


Figure 12: Comparison of result obtained by PID tuned with different techniques and fuzzy controller when HR=85

6. CONCLUSIONS

Heart Rate signals are used as a reliable indicator of heart diseases. These HR signals form the basis of functioning of a pacemaker. Pacemaker performance depends not only on sensors and the pacemaker circuitry but also on the performance of the controller. In the present work different control techniques are analyzed to design Heart Rate controller. Initially a PID controller is tuned with the help of Zeigler- Nichols, Tyreus-Luyben and Relay method respectively to satisfy the different performance parameters. The PID controllers thus tuned do not provide the overall satisfactory response. Therefore to improve the performance of the system, an intelligent fuzzy controller is designed with the help of different rule base and knowledge base. It is observed from the response of fuzzy controller that all the parameters (rise time, settling time, maximum overshoot are within the limits and a smooth and satisfactory response is obtained. Therefore it is concluded that the overall performance of fuzzy controller is better as compared to the PID controller.

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