Design and Stability Analysis of an Adaptive Neuro-Fuzzy Inference System (ANFIS) Based Pacemaker controller in MATLAB Simulink

Asghar Dabiriaghdam  
Islamic Azad University

Nader Jafamia Dabanloo  
Islamic Azad University

Fereidoun Nooshiravan Rahatabad  
Islamic Azad University

Keivan Maghooli  
Islamic Azad University

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ABSTRACT
This paper presents the design and stability analysis of an Adaptive neuro-fuzzy inference system-based controller of a pacemaker in MATLAB Simulink. ANFIS uses Learning and Speed properties of Fuzzy and Neural Networks. Based on body states and preprogrammed situations of patients (age and sex, etc.), heart rate and amplitude of pacing pulse are changed. Output signal that is fed back from heart is compared to the reference fuzzy bases ANFIS signals. After designing ANFIS based controller, the stability of the proposed system has been tested in both Time (Step response) and Frequency domains (Bode Diagram and Nichols chart). In our previous paper Step response analyzed and compared with other works. For frequency domain, all the possible frequency analysis methods have been tested but because of nonlinear properties of ANFIS, after linearization, just the Bode diagram achieved good results.

The step response results in time domain is compared with previous work’s results including optimum heart pulse rate for each particular patient. In frequency-domain the Bode diagram stability analysis showed Gain and phase margin as follows:
GM (dB) = 42.1 and PM (deg) = 100

1. INTRODUCTION
ANFIS as a fuzzy logic method is used for generating signals and approximation of predefined functions and control of miscellaneous engineering systems like civil, electrical and biomedical engineering. For instance, electrical motor drives (AC and DC) and social engineering problems [1,2]. A pacemaker uses electrical impulses to contract the heart muscles, to adjust the heart rate.
To provide rapid response, the first 10 second is considered for design of rate controllers. Microelectromechanical systems (MEMS) accelerometers and motion sensors (gyroscopes) placed in a pacemaker detects movement and patient’s physical activity requiring an increased heart rate and generates a signal that is proportional to physical activity [3,4,5].
This paper presents the design and stability analysis of an adaptive neuro-fuzzy inference system-based controller of a pacemaker in MATLAB Simulink. ANFIS uses Learning and Speed properties of Fuzzy and Neural Networks to adjust output heart rate that has been trained by a step response of the system and Neural Networks to calculate coefficients of Membership Functions (MF).

2. CONVENTIONAL CONTROL SCHEME FOR PACEMAKER SYSTEMS
Conventional and fuzzy PID control design has been demonstrated by Wei Vivien SHI [3], [5]. The
fuzzy control concept is used to design a controller for a system that is difficult to model due to nonlinearities and other modeling complexities [6,7]. The fuzzy control has the ability of transforming linguistic and expert knowledge and information into control signals. The block diagram of Shi’s work is shown in Figure 1.

![Figure 1 Design of fuzzy PID controller for dual-sensors cardiac pacemaker system](image1)

2.1. ANFIS controller design for Pacemaker Systems

A signal from the output ECG signal is fed back and compared in an ANFIS based controller. ANFIS compared with other fuzzy control algorithms provides a better control scheme for estimation and generation of pacing pulse’s rate and amplitude.

3. ANFIS CONTROLLER DESIGN

3.1. ANFIS Concept

ANN has learning capabilities and Fuzzy logic has a good capability of interpretability. ANN can be used to learn the membership values for fuzzy systems, to construct IF-THEN rules, or to construct decision logic. The structure of the ANFIS model is a graphical representation of the TS-FLC model. The ANFIS structure for control of any plant is presented in this section. The functions of the various layers are given in the form of an algorithm as described below. The structure contains the same components as fis, except for the NN block. The ANFIS (Figure 2) is tuned automatically by the least-square-estimation and the back-propagation algorithm [8].

![Figure 2 ANFIS with one input and one output](image2)

3.2. ANFIS learning methods:

Considering that the learning data will be given from patient ECG parameters, the online method of receiving the data will not be useful. Instead, offline data from healthy people with similar parameters of patient (Age - Sex - Rest-walking and etc.) or patient at earlier stages of the patient disease will be used to train ANFIS.

Offline learning methods are:
1. Grid Partitioning:
2. Subtractive clustering:
3. Fuzzy C Means (FCM):

Methods one and two are investigated in our earlier work [9]. FCM method has been used in this paper and compared with other methods. FCM convergence speed is very faster than the other two methods.

3.3. ANFIS controller design by FCM method and comparison with Grid Partitioning Subtractive clustering

Because the FCM method is not available in MATLAB toolboxes, we have used the code developed by Dr. Kalami to realize FCM. The output of the script is shown in Figures 3, 4 and 5.
The minimal training root mean square error (RMSE) calculated was:
RMSE = 2.7251

4. SIMULATION AND STABILITY ANALYSIS OF ANFIS BASED CONTROLLER IN SIMULINK

In this work two stability analysis methods are tested:
1. Time domain analysis
2. Frequency domain analysis

4.1. Heart Models
There are a lot of heart models including mathematical [17,18,20] and electrical (Vanderpol and modified Vanderpol equations) [14,15,16] and YNI mathematical physiological model (Yanagihara, Noma, and Irisawa) [22] and IPFM [18,19] and Vanderpol Oscillators were developed within 20 last years.

We have chosen transfer function model [13] in current working.

4.2. Stability analysis in time domain by Step Response method
The simulation of the designed controller shown in Figure 6. First the training data generated in a conventional PID heart controller. MATLAB PID feature used for optimization of step response of heart model then the in1 as input and in3 as output signals exported to workspace of MATLAB(ver.14) for the training purpose.

After training, data are entered to the MATLAB ANFIS GUI toolbox. Load data is used to input training data and generate FIS with Grid
partitioning and hybrid back propagation and recursive least square as optimization method.

But because of increasing speed, we used FCM that is not available in MATLAB ANFIS GUI toolbox (Section 3.3).

The pacemaker and heart models shown in equations (1) and (2) as in [13]:

\[
\frac{8}{s + 8} \quad (1)
\]

and the heart model is chosen as given by the following:

\[
\frac{169}{s^2 + 20.8s} \quad (2)
\]

After the rule base is specified, the ANFIS adjusts only the MFs of the antecedents and the consequent parameters. The BP algorithm can be used to train both the premise and consequent parameters. Then pressing Train now starts design and optimization of input and output MF by hybrid methods described above. If we chose number of input MF’s a large number (>500) it lasts very long time for MF’s to be optimized (a couple of hours in a Lenovo laptop with 16GByte of RAM, especially if we have more than two Input and Output (the curse of dimensionality). But by using FCM, these problem rectified and speed increased considerable. After we got an acceptable error (0.38 at this research), we saved the generated FIS file and we can test it by using ‘Test Now’ button. Then the optimized fis file used in Fuzzy logic control box in SIMULINK.

Figure 7 shows Step response parameters (Rise time, Overshoot, Settling Time) in time domain. The lower block in Figure 6 shows ANFIS controller with FLC box with FIS file generated during training phase of ANFIS edit GUI toolbox or FCM MATLAB code.

After running the SIMULINK, with the step input of 85 bpm, comparison of the results is shown in Table 1.

Table 1 Comparison of results with Step input

<table>
<thead>
<tr>
<th>Type</th>
<th>RMSE</th>
<th>MAX. Error %</th>
<th>Max. Overshoot%</th>
<th>Rise Time(s)</th>
<th>Settling Time(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FPID [3]</td>
<td>0.889</td>
<td>1.72</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Fuzzy [3]</td>
<td>2.380</td>
<td>4.88</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>ANFIS [9]</td>
<td>0.14</td>
<td>1.4</td>
<td>1.08%</td>
<td>1.7</td>
<td>1.55</td>
</tr>
<tr>
<td>PID [3]</td>
<td>0.16</td>
<td>2.03</td>
<td>5.85</td>
<td>1.43</td>
<td>9.88</td>
</tr>
<tr>
<td>REF [13]</td>
<td>NA</td>
<td>NA</td>
<td>3.5</td>
<td>0.27</td>
<td>0.76</td>
</tr>
<tr>
<td>Fuzzy [21]</td>
<td>1.034</td>
<td>4.88</td>
<td>0</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>

Figure 6 ANFIS and PID controller simulation using SIMULINK

Figure 7 Step response of conventional PID and ANFIS controller with HR=85 bpm
4.3. Stability analysis by changing forward path gain:

System forward path gain varied from 1 to 30 on both PID and ANFIS controllers (Figure 8). Near gain of 30 and more system started to show instability. For PID controller this happened sooner. Instability seen on both timed unity step and frequency responses (Bode diagram). The responses shown in Figure 9.

5. STABILITY ANALYSIS AT FREQUENCY DOMAIN BY BODE DIAGRAM METHOD

By using Simulink Bode diagram tool and linearization of fuzzy block, stability of the ANFIS controller investigated by calculating gain and phase margin parameters.

As shown at Figure 10, the designed controller system at closed loop feedback is stable. Gain and phase margin parameters at three simulation times (0-10-30th sec.) are:

Gain Margin = 42 dB
Phase Margin = 100 deg

6. DATASETS:

Data sets used from real and artificially generated ECG data. Real Data set for input reference has been chosen from following databases:

6.1. Real Data

1. The Massachusetts Institute of Technology-Beth Israel Hospital Arrhythmia Database
2. The European Society of Cardiology ST-T Database (90 records, two hours each)
3. The Noise Stress Test Database (12 records, 30 minutes each)
4. The Creighton University Sustained Ventricular Arrhythmia Database (35 records, 8 minutes each)
5. Pacemaker recorded diagnostics database
6. The American Heart Association database for evaluation of Ventricular Arrhythmia Detectors

6.2. Synthetic Data generated by MATLAB code

These data generated by this method described at (ECGHOSM) ECG Heterogeneous Oscillator Simulation Model [10]. The main m file contains two sections; the first section corresponds to the generation of realistic twelve lead free-noise ECG waveforms with artificial RR-tachogram. In this section (free-noise case), we can obtain the RR-intervals from the synthetic ECG using a simple algorithm to detect local maxima. For ECGs with noise may be necessary to use more complicated methods. The second section is related to the generation of realistic 12 lead noisy ECG waveforms with artificial RR-tachogram.

6.3 Image data converted from stress test equipment manufactured by AVICINA company:

These data generated from image files (JPG format) from AVICINA stress test equipment. They are converted to the MATLAB datasets by image processing techniques. The converted data shown in Figure 11:

6.4. Data collected from Mi-Band smart watch and the 5s apple mobile phone:

Both accelerometers’ data from mobile phone and heart rate from smart watch gathered together. Because sample rates were different, they are resampled and used as input data to the ANFIS controller and the PID controller. Collected from at the mobile phone and the smart watch and resampled data shown in Figures 12,13,14.

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1http://www.avecinna.com/
(Dr. Birjand Talab work²):

The data downloaded from Dr. Birjand Talab work at [11], [12] Dallas University database that collects HR and Spo2. Figure 15 shows system and various stages of data including relaxation, walk, run, stress and so on. Response parameter of the ANFIS controller with various reference heart rates

1.First relaxation time: 5 minutes.
2.Physical stress: Stand for 1 minutes. Standing, walk on a treadmill at 1miles /hour speed for two minutes. Then walk-jog on a treadmill at 3 miles/hour for two minutes.
3.Second rest: five minutes.
4-Cognitive stress: three minutes
5-Third relaxation: five minutes.
6-Emotional stress: five minutes.
7-Forth rest: five minutes

7.RESULTS AND DISCUSSIONS

7.1. Comparison of PID and fuzzycontroller simulation results

7.1.1. Time domain

Jyoti et al. compared a fuzzy and PID controller with Ziegler-Nichols, Tyreus Luyben, and Relay methods; the work showed that the fuzzy controller had a maximum overshoot less than all of the tuned PID controllers and improved rise and settling time than other three methods [13].

7.1.2 Frequency domain

There is no data for frequency domain stability analysis available to be compared with our ANFIS method. All of the previous works are done based on Time domain techniques.

8. CONCLUSION

First the controller system design by PID method and then tuned automatically by MATLAB PID

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²https://personal.utdallas.edu/~birjandtalab/Data.html
tune toolbox. The training data extracted and used as input to ANFIS toolbox. Various Stability Analysis methods including Time and frequency methods tested. Finally, because of nonlinear nature of ANFIS, bode diagram and Step response methods chosen. Heart rate (HR) is used as a reliable indication of heart diseases. HR forms the basis for functioning of a cardiac 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 investigated to design an intelligent heart rate controller. Initially a PID the controller tuned with the help of MATLAB tune GUI tool to satisfy the different performance parameters.

To improve the performance of the system, an intelligent ANFIS controller is designed with ANFIS toolbox, it is observed from the response of fuzzy controller that the designed parameters (maximum overshoot and RMS error and maximum error) of ANFIS controller is better as compared to the conventional PID controller and other methods.

DECLARATIONS:
ETHICAL APPROVAL:
N/A

COMPETING INTERESTS:
There is no conflict of interests

AUTHORS’ CONTRIBUTIONS:
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