Intelligent Fractional-Order PID (FOPID) Heart Rate Controller for Cardiac Pacemaker

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Abstract—Efficient and robust control of cardiac pacemaker is essential for providing life-saving control action to regulate Heart Rate (HR) in a dynamic environment. Several controller designs involving proportional-integral-derivative (PID) and fuzzy logic controllers (FLC) have been reported but each have their limitations to face the dynamic challenge of regulating HR. Fractional-order control (FOC) systems provide controllers that are described by fractional-order differential equations that offers fine tuning of the control parameters to provide robust and efficient performance. In this work a robust fractional-order PID (FOPID) controller is designed based on Ziegler-Nichols tuning method. The stable FOPID controller outperformed PID controllers with different tuning methods and also the FLC in terms of rise time, settling time and % overshoot. The FOPID controller also demonstrated feasibility for rate-adaptive pacing. However, the FOPID controller designed in this work is not optimal and is limited by the tuning procedure. More efficient design using optimization techniques such as particle swarm intelligence or genetic algorithm tuning can offer optimal control of the cardiac pacemaker.

I. INTRODUCTION

Heart diseases are the leading cause of death in the US and the world [1]. Technological advancement to improve human lives especially in the field of cardiovascular systems has progressed immensely since the introduction of cardiac pacemakers saving thousands of lives. Medical device (i.e. cardiac pacemaker) implanted within a patient’s chest senses abnormal heart beat caused by arrhythmias and sends electrical control signals to simulate the heart muscles thereby regulating the performance of the heart. Robust dynamic control system design is desired to improve the efficacy of the cardiac pacemaker and several researchers have addressed the control system designs for the pacemaker. This work is based on the control system design for an intelligent heart rate controller that uses proportional-integral-derivative (PID) and fuzzy logic controllers (FLC) [2]. The authors provided various simulations for PID controllers and FLC and concluded that FLC outperformed PID controller on the basis of various performance measurements such as % overshoot, rise and settling times for step input of heart rate (HR).

The classic PID controller is not optimal in providing the desired control strategy. This is because of using fixed control parameters in the feedback system. While active research progresses in improving the PID design, challenges will continue to exist on performance parameters such as % overshoot, rise and settling times [3]. FLC gain importance from its ability to express uncertain information (ambiguity) and the reasoning introduced in control decision providing scope for both adaptive and robust controller design [4]. Nevertheless FLCs have several drawbacks such as manual tuning, performance-robustness tradeoff, several localized parameters, linguistic variables, look-up table implementation, dimensionality issues etc. which makes them impractical in many applications [4]. Researchers have also attempted to design the combined mode of fuzzy-PID controller for various applications, but there are limitations to the performance parameters and efficient implementation of such combined design [5].

Fractional order control (FOC) is the generalization of traditional controllers or control schemes to non-integer orders. FOC applications received a widespread interest since it use more tuning parameters thus offering more adjustable time and frequency responses of the control system, allowing the fulfillment of robust performances. The practical advantages for FOC is to provide more flexibility and insight in control design and thus give a clear-cut approach for designing robust control system [6-7]. With the strong mathematical theory involving fractional calculus and fractional order differential equations, the robust design of fractional-order PID (FOPID) controller can achieve better performances than conventional PID controller and FLC [8-10].

The following section will give a brief overview of FOPID controller design. The general transfer function \(C(s)_{\text{PID}}\) of a PID controller can be described as below:

\[
C(s)_{\text{PID}} = K_P + \frac{1}{T_I s + T_D s},
\]

where, \(K_P\) is proportional constant; \(T_I\) is integral constant; and \(T_D\) is derivative constant. The FOPID controller modifies the transfer function with non-integer orders for the integral and derivative terms as below:

\[
C(s)_{\text{FOPID}} = K_P + K_I s^\lambda + K_D s^\delta
\]

where, \(K_I\) and \(K_D\) are integralsize constants; \(K_I\) is derivative constant; and \(\lambda\) and \(\delta\) are positive real numbers (not necessarily integers) for the integrator and differentiator respectively. Hence, when \(\lambda = \delta = 1\), the transfer function \(C(s)_{\text{FOPID}} = C(s)_{\text{PID}}\). Therefore, the fractional order PID controller generalizes the integer order PID controller and expands it from the point to the plane, as shown in Fig 1.
Hence, with more tunable parameters, this expansion adds more flexibility to controller design and improves efficacy to control several real world processes more accurately. In this work, the authors aimed to design and implement a FOPID controller based on Zeigler-Nichols method for the cardiac pacemaker design that was previously published in [2]. The authors also compare the performance of the new FOPID controller with PID and FLC based on % overshoot, rise time (t_r) and settling time (t_s) for step variations of the HR.

The equivalent integer-order transfer function was computed for simulation. The performance was measured as follows:

\[ R(s) \rightarrow 8 \quad (s + 8) \quad 169 \quad (s^2 + 20.8s) \quad Y(s) \]

FIG 2. Block diagram of the CL system for the cardiac pacemaker using FOPID controller as published in [2].

C. Simulation Environment

MATLAB/SIMULINK software is used for all simulations. The MATLAB toolbox FOMCON for fractional order modeling and control is used for the design and implementation of the FOPID controller and display the response to various inputs. The controller was exposed to series of step inputs and sinusoidal variations in HR and performance were evaluated based on t_r, t_s and % overshoot.

III. RESULTS

A. PID Controller Tuning using Z-N tuning method:

The values for the critical gain \( K_C = 3.54 \) and critical period \( P_C = 0.4874 \) (s) were obtained using Z-N tuning method. The PID parameters for Z-N tuning methods are \( K_P = 2.124; \quad T_I = 0.2437 \) (s); \( T_D = 0.0609 \) (s) and the corresponding transfer function was estimated for simulation. Fig 3 shows the amplitude of the CL response of the pacemaker with reference HR = 65 bpm. The performance was measured as follows: rise time \( t_r = 0.1027 \) s, and settling time \( t_s = 1.429 \) s with 60% overshoot.

B. PID Controller Tuning using T-L tuning method:

The PID parameters for T-L tuning method are \( K_P = 1.6091; \quad T_I = 1.0723 \) (s); \( T_D = 0.0774 \) (s). The transfer function was derived for these parameters and the amplitude of the CL response for unit step and reference HR = 65 bpm is shown in Fig 4. The performance was measured as follows: rise time \( t_r = 0.1297 \) (s), settling time \( t_s = 1.423 \) (s) with 24.5% overshoot.

C. FOPID Controller Tuning:

The FOPID design yielded the following parameters:

\[ K_P = 1.17; \quad K_I = 0.27 \quad (s); \quad K_D = 0.21 \quad (s); \quad \lambda = 0.97; \quad \text{and} \quad \delta = 0.95. \quad (3) \]

The equivalent integer-order transfer function was computed for simulation. The performance was measured as follows:
rise time $t_r = 0.1367$ (s), settling time $t_s = 0.2761$ (s) with 2.05% overshoot. Fig 5 shows the amplitude of the CL response to unit step and reference HR of 65 bpm.

Fig 6 shows the response of the FOPID controller to series of step inputs mimicking dynamic change in the HR stimulus based on the person’s behavior. The HR is varied from 65 to 175 bpm to test the performance of the FOPID controller for such huge swings in HR that can be achieved, for instance, during exercise.

Table 1 compares the performance of different controllers based on rise time, settling time and % overshoot reported in [2] (PID_A design with Z-N, T-L and relay tuning and Fuzzy controller) with the PID design reported in this work (PID_B with Z-N, T-L tuning and FOPID controller based on Z-N tuning method. As seen from the table, performance of FOPID controller outperformed all other designs overall with lower settling time and % overshoot and comparable rise time which is the desired response for cardiac pacemaker control for life saving action thereby demonstrating robust pacemaker control system design for HR.

![Fig. 3. Response of closed loop PID system with Z-N tuning for HR = 65 bpm](image3)

![Fig. 4. Response of closed loop PID system with T-L tuning for HR = 65 bpm](image4)

![Fig. 5. Response of CL FOPID system for HR = 65 bpm](image5)

![Fig. 6. Response of the CL FOPID system for series of step-input HR stimulus; Grey line is the step input and blue line is the controller response.](image6)

![Fig. 7. Response of the CL FOPID system for sinusoidal oscillations type HR stimulus; Grey line is the step input and blue line is the controller response.](image7)
overall provides a robust design for practical use in many applications.

The FOPID controller based on fractional calculus allows finer tuning of the controller parameters allowing more robust control. Extensive knowledge is required in fractional calculus for FOPID design which can provide great insights into efficient tuning. Also, non-integer order transfer function has to be converted to its integer-order equivalent to obtain the system response which is not a significant challenge with the availability of various approximation methods, fast computer, higher memory and speed. The controller tuning used in this work is purely heuristic based on Z-N tuning. The use of optimization techniques, such as particle swarm optimization or genetic algorithm [8, 11-12] can provide efficacy in the choice of optimal parameters for the FOPID design, which is the future step of this work.

V. CONCLUSIONS

A robust FOPID controller based on Z-N tuning method was designed for cardiac pacemaker to regulate the HR. The FOPID controller displaced the complexities and limitations with other designs and outperformed offering huge promise which is also feasible for rate-adaptive pacing. The FOPID tuning procedure can be optimized using particle swarm intelligence or genetic algorithm as future work.

REFERENCES


