Sudden Cardiac Death Prevention Using a Pacemaker

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***Abstract*— Sudden cardiac death is the most common and often first indication of coronary heart disease and in the United States alone, SCD accounts for approximately 300,000 to 400,000 deaths every year. In order to improve patients' quality of life, this sudden and unexpected death caused by loss of heart function can be minimized through the implementation of a pacemaker. Since the cardiovascular system is considered to be a closed loop system with filter and controller with unity negative feedback, a proportional, integral, and derivative (PID) heart rate controller was used for the pacemaker model. By using Simulink, a MATLAB-based graphical programming environment for modeling, simulating and analyzing multi-domain dynamical systems, the pacemaker was tested using a slow heart rate, i.e. bradyarrhythmia. The heart rate input used was slower than normal. After running through the PID controller, this slow heart rate would then increase to a normal heart rate above the set point of 60 beats per minute. It was found that the pacemaker design was successful in adjusting the slow heart rate to a normal heart rate.**

***Clinical Relevance*— This establishes a better explanation into how a pacemaker can function given certain heart rate fluctuations, which, in this case, was looking specifically at patients with bradyarrhythmia.**

I. INTRODUCTION

In a healthy heart, the Sinoatrial (SA) node acts as the pacemaker of the heart by periodically generating electrical pulses that can cause muscle contraction [1]. This electrical pulse also causes both atria to contract forcing blood into the ventricles [1]. The electrical conduction is then delayed by the Atrioventricular (AV) node to allow the ventricles to fully fill, before the His bundle around the heart spreads the electrical activation within the ventricles, causing simultaneous contraction pumping the blood outside of the heart to the rest of the body [1]. Due to aging or disease, the conduction abilities of the heart may change causing anomalies of the heart rate such as tachycardia (fast heart rate) and bradycardia (slow heart rate) [1]. Bradycardia may occur as a result of failure of impulse generation with anomalies in the SA node, or as a result of failure of impulse propagation in which the conduction from atria to the ventricles is delayed or blocked [1]. Sudden cardiac death as a result of severe bradycardia, asystole, or pulseless electrical activity are the most common in severely diseased hearts [2]. Some risk factors of SCD include age, hypertension, left ventricular hypertrophy, intraventricular conduction block, smoking, and relative weight [2].

In order to reduce the risk of SCD, implantable pacemakers have been developed to deliver external electrical pulses to maintain an appropriate heart rate [1]. Pacemakers normally have two leads fixed to the wall of the right atrium and right ventricle [1]. By using a pacemaker, it may be able to prevent SCD due to bradyarrhythmia, which is characterized by slow heart rate, and in certain circumstances such as torsade de pointes, which is associated with congenital long-QT syndrome (LQTS) and pause-dependent ventricular tachycardia (VT) [3]. In order to prevent such behavior, we proposed to design a single chamber pacemaker that senses, paces, and activates only the atrium by using a heart rate PID controller. The main function of an artificial pacemaker is to stimulate the heart muscles to regulate the heart rhythm [4]. It consists of two functional units, with the first being the "sensing circuit" that senses a patient's heart rate and the second being the "output circuit," which then transmits the electrical signals to the heart muscles in order to control the patient's heart rate [4].

The cardiovascular system is considered a closed circuit system since blood is always enclosed within vessels and the heart as it circulates throughout the body [5]. As such, it can be modeled using a filter and PID controller with unity negative feedback [4]. The PID controller is a conventional controller that inputs an error signal, which is the difference between the measured process variable and the desired set point [4]. In this case, the error signal is a slow heart rate and the desired set point is the normal heart rate of 60 beats per minute. The controller then modifies the process control inputs by reducing the error signal [4]. In order to adjust the reactions of the controller to the setpoint changes and unmeasured disturbances, the value of PID parameters must be tuned accordingly [4]. The PID controller design is made up of three separate parameters: proportional, integral, and derivative gain. The proportional gain reaction is based on the error signal's current value, the integral gain is based on the sum of recent errors, and the derivative gain is based on the rate of change of the error signal [3]. The weighted sum of these three parameters are utilized in order to adjust the heart rate [4].

II. METHODS

A. DESIGN OVERVIEW

i. Performance Goals and Constraints

The overall goal of our project was to study, recreate and test an effective pacemaker closed loop control system. We wanted to determine the transfer functions of the controllers which minimizes the error between the target and actual heart rate to ensure that the person's heart rate remained within a set "healthy" range. The healthy range for the heart rate of an adult is from 50 to 70 beats per minute [4]. Our pacemaker was calibrated to this range to signal the PID controller that it did not need to make any adjustments.

The biggest operational constraint within our design model was that the system remains as a closed loop system because the cardiovascular system as a whole was assumed to be closed loop at all times [3].

ii. Pacemaker Signaling Process

Pacemakers send electrical stimulus signals to stimulate the heart to beat faster for bradycardia patients [4]. The fixed signal is sent to the two nodes that the pacemaker is connected to on the heart, and the PID controller is used to help with overshooting the heart rate and when it is in steady state. When overshooting of the heart beat occurs, there are big fluctuations that can be very damaging to the heart.

For the pacemaker signaling process, we first wanted to measure the time interval between the two R peaks in the QRS complex of the electrocardiogram (ECG) signals. Taking the two R peaks, we can calculate the time difference and heart rate. By establishing a target time interval, the pacemaker can indicate whether the heart rate is normal or needs adjustments [4]. The pacemaker can then sense if the heart is beating too fast or too slow. If the difference between the target time interval and the measured time interval is less than 0, then the output circuit will send a signal to the PID controller to speed up. In the case that the difference between the target time interval and the measured time interval is greater than 0, then the output circuit will send a signal to the PID controller to slow down the heart. We will now have a new RR time interval after the PID controller signal tries to adjust the heart back to a normal rate. With the new time interval, we subtract that from the target time interval, which results in the margin of error in the heart rate that still needs to be adjusted by the PID controller. If the difference and the error is equal to 0, we will then know that the heart rate is back to normal. And if it is not 0, the continuous feedback loop will continue to make the adjustments needed [4]. The pacemaker will once again sense if the heart rate is too high or too low and it will go to the PID controller to make the necessary adjustment. In our specific model, the pacemaker was only taken into account.

B. BLOCK DIAGRAM

iii. Assumptions

Initially the heart rate was stimulated from the beginning of the block diagram before proceeding through the pacemaker, which acts as a sensor to determine whether the signal is too low or high of value. Once the signal was sent through the pacemaker, it then continued on through the PID controller to detect the level of adjustment that the heart rate will need to be normalized to. This normalized heart rate and value was then sent back to the heart in a closed-loop format to retrieve the desired heart rate.

- Ideal feedback
- Pacemaker is always on
- Pacemaker acts as a low pass filter (frequency in, frequency out)
- Average heart rate is 50 - 70 bpm
- Conduction of the heart is described by Ohm's Law (constant resistance and voltage throughout heart)

In order to simplify our system to properly set up a Simulink model in MATLAB, a few assumptions had to be made. The Simulink model and the pacing of the heart rate was assumed to have a continuous signal where the pacemaker would adjust the heart rate to either speed up or slow down the pacing of the signal. The model of the pacemaker was assumed to have a transfer function that allows low frequencies, where there will be a low pass filter transfer function. It was also reported that a pacemaker would determine the average heart rate to be 50 to 70 beats per minute [6]. The overall cardiovascular model would be expected to be an underdamped second order system where the individual has pre-existing heart conditions and require the usage of a pacemaker. Similar to Ohm's Law for conduction, the resistance value that was set would be at the value of 100Ω and the voltage value set would be at 2.8V [6]. The lead placement of the block diagram and Simulink model remain consistent throughout and unchanged from their initial positions. This overall setup was catered towards individuals with pre-existing heart conditions that require an implementation of a pacemaker to regulate their heart rate and their abnormalities.

iv. Diagram

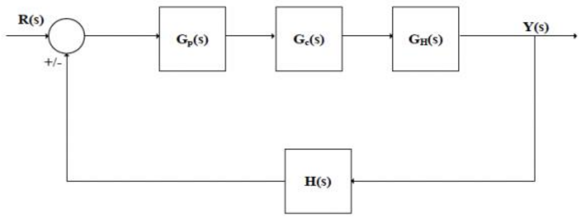

Figure 1: *General block diagram of the heart rate PID controller for a single chamber pacemaker.*

$$R(s) = actual\ heart\ rate$$

$$G_p(s) = pacemaker = \frac{8}{s+8}$$

$$G_c(s) = controller = PID$$

$$G_H(s) = heart = \frac{169}{s^2 + 20.8s}$$

$$I(s) = \frac{V}{R}\text{ (Ohm's Law)}$$

$$H(s) = feedback = 1$$

$$Y(s) = desired\ heart\ rate$$

Since we were given the transfer functions of the pacemaker and biosystem (heart), there was no need for us to take the Laplace of a time domain. Another portion of the biosystem for this model also included the conduction properties of the heart which can be simplified as a simple circuit where the conduction of the current through the heart can be represented using Ohm's Law.

C. SIMULINK MODEL

The Simulink model, seen in Figure 2, was used to model how the heart rate changes through initial detection within the pacemaker, through the PID controller and to the biosystem, which consists of the heart and its electrical conduction property described by Ohm's Law. The transfer functions for the pacemaker and heart biosystem came from the literature found in research [4]. For this specific pacemaker simulation, we made the desired set point for heart rate be 60 beats per minute. The results from this set point are shown in the next section. A frequency (desired heart rate) was inputted into the system.

III. RESULTS

A. Simulink Results

Through fully testing the pacemaker, PID controller, and feedback controller model, the system began with an initial starting point at 60 beats per minute. The input that follows through the pacemaker then has a stimulation duration between 1 to 2 seconds with a set input that can be accounted for through the time delay as the system has an exponential plot. Once the pulse occurred, the exponential behavior of the plot then had a time delay, in which the amplitude of the response would slowly plateau and stabilize back to its original starting point of 60 beats per minute. There is a significance in finding a consistent medium of value between the pulse rate and the duration points of the heart rate as the oscillations occurred. From the plotted model results the heart rate would be predicted to have larger overshoots of

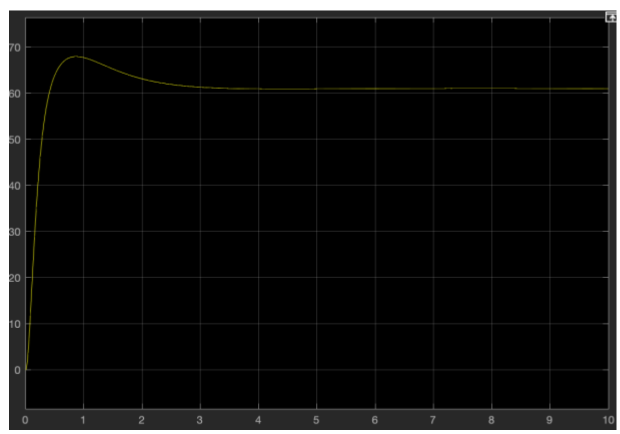

Figure 3: *Simulink plot after running a slow heart rate through the pacemaker to achieve a heart rate above the set point of 60 beats per minute.*

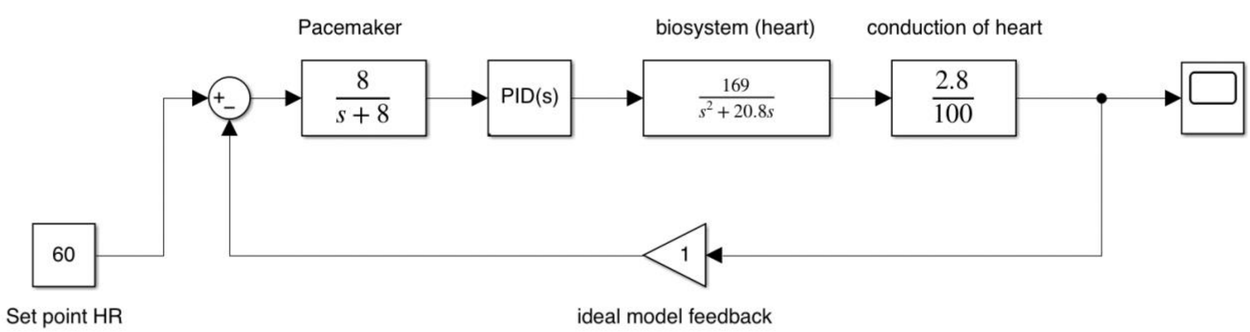

Figure 2: *Simulink block diagram of the heart rate PID controller for a single chamber pacemaker.*

oscillations as time continued. This would be attributed to the constant exhaustion on the heart, as well as the pacemaker's behavior as the system continuously ran. Once the continuous signal and normalized heart rate progresses the closed-loop system will then regulate the pacing and feedback, which entails that the heart rate if too high or too low will eventually succumb to the original set point as its output, being 60 beats per minute.

B. SENSITIVITY ANALYSIS

Stability analysis would be progressed through calculating the transfer function of the overall system and implementing ECG data found from patients or individuals with pre-existing health conditions. These patients would undergo clinical trials where we would perform an ECG test trial on the individual and through the test the we would implement those ECG data points into the Simulink model as the input before going through the pacemaker. This implementation would allow for all simulations to be set at a steady state of 60 beats per minute with a small time duration within the Simulink.

C. ERROR ANALYSIS

Possible errors in the simulation include not properly tuning the PID controller in the time domain to minimize the error signal, as well as not filtering out the noise from the controller in the Simulink model. On with the feedback noise there could also be resistance within the heart and its impulses that were not fully accounted for, as the computational aspect of the pacemaker has a more complex mechanism than the controllers that were implemented.

IV. DISCUSSION

Our simulation of the pacemaker is consistent with the physiological observations because after inputting the slow heart rate through the pacemaker model, it was able to reach our set point, which was our desired heart rate of 60 beats per minute.

The use of our simulation as an alternative to actual physiological experimentation is that the closed loop system allows for the pacemaker to signal and correct the heart simultaneously. In a physiologic experiment, we would be able to measure for the changes in the heart beat, but there are limitations when it comes to sending a signal to correct the heart beat. Through our closed loop system with the pacemaker and PID controller, we are able to speed up the heart rate of bradycardic patients because there are nodes directly connected to the heart sending signals to speed up. These advantages in our system can help bradycardic patients more efficiently, so that enough blood continues to pump through the patient's body. The pacemaker acts as a low pass filter,

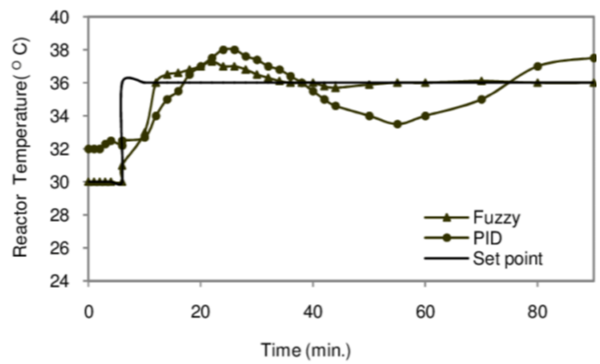

Figure 4: *Simulink plot after running a slow heart rate through the pacemaker to achieve a heart rate above the set point of 60 beats per minute.*

which then goes to the PID controller to signal the heart to speed up or slow down [4].

Similarly to a PID controller, a fuzzy logic controller (FLC) can also be used to regulate heart rate with a low pass filter [4]. After inputting a slow heart rate, it is expected that a fuzzy controller can produce similar, if not more accurate, results to a PID controller [7]. In general, FLC's are more efficient than the PID controller because they are less sensitive to changes in system parameters and result in lower system energy consumption, as shown in Figure 4 [8].

The pacemaker as a device gives a huge advantage to those with non life threatening and life threatening heart defects to live a normal and comfortable life, however a limitation to these devices is its life span of 8.5 years. For our model, the use of a PID controller is an advantage as it reduces steady state error, overshoot, and settling time of the output, which allows the simulation of the heart to be more exact in performing the desired heart rate [4]. Some limitations to our current model is that some natural noise may interfere with the heart rate signal that the pacemaker receives causing some inconsistencies with the patient's actual heart rate. Another limitation of our model is that we assume that the heart is a perfect circuit with a single resistance throughout. In reality, this is not the case as the resistance depends on the ion flux throughout the different chambers within the heart.

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