Application of Control Systems in Artificial Cardiac Pacemaker

Abstract— **Control systems are largely prevalent across both mechanical and physiological systems.**

In this report, we aim to study the intersection of the two by modelling and simulating the control system of a pacemaker regulated functioning heart. The model uses some basic assumptions and has been simplified to a closed loop feedback system which contains a PID controller. The controller tuning was done using Simulink (MATLAB) to obtain a quick rise time, low offset, reduced oscillations and low overshoot. Additionally, an accelerometer was used to simulate a load on the heart that would increase the set point above 60 bpm, such as engaging in physical activity. It was found that the modeled pacemaker system was able to successfully adjust heart rate to these changes in set points.

INTRODUCTION

Heart is one of the most important organs of a human body which need to work continuously and steadily for a living organism's metabolism to function properly. Therefore, individuals susceptible to abnormal heart rhythms require additional systems to help their heart function normally. One such device used is an artificial pacemaker. The pacemaker senses abnormal heart rhythms (bradycardia or tachycardia) and emits electrical impulses to stimulate the heart muscles accordingly and maintain a normal heart rhythm.

The pacemaker performs two main functions: sensing and pacing. A combination of accelerometer, minute ventilation and cardiac contractility sensor enables the pacemaker to provide an immediate response to any physical activity and detect the metabolic need. The electrodes are also able to sense contraction force of the ventricle's chambers and predict how fast the heart needs to contract to maintain the cardiac output. The pacing action of the pacemaker is performed by electrodes attached to the ventricles or the atria of the patient.

ASSUMPTIONS

Biocompatibility: It is assumed that the body accepts the pacemaker system and that there is no hindrance in the electrical signal propagation due to physiological complications.

Zero lag: It is assumed that there is no lag within the system i.e. no time delay between sensing the current heart rate and the actual contraction of the heart after the signal is transmitted.

MODELLING

With the previously stated assumptions, a simplified model of the Pacemaker-Heart system with an input signal from an accelerometer can be built.

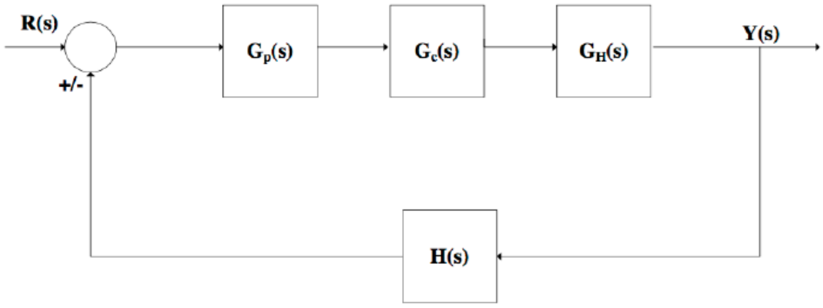

Figure 1

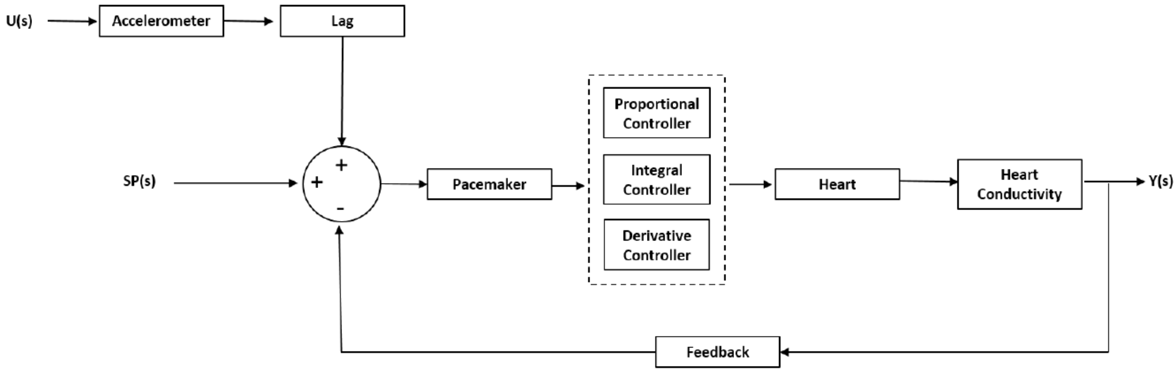

Figure 2

The model comprises of a load which acts on the accelerometer, a set heart rate at which the pacemaker operates, a pacemaker, a PID controller, heart (modelled in term of its cardiovascular function and its electrically conductive properties). The pacemaker-heart closed system receives the set point which outputs the heart rate at which the heart is beating. The heart rate set point is increased with an increase in physical activity by the accelerometer. The lag that has been introduced in the system is to model the time delay of the accelerometer.

Pacemaker-Heart Model

The closed loop transfer function shown in figure 1 comprises of the heart, pacemaker, and PID controller where G_p (s) is the transfer function of the pacemaker, G_c (s) is the transfer function of the PID controller, and G_H (s) is the transfer function modelling the cardiovascular function of the heart. Using the voltage V of the pacemaker, the current running through the heart I, and R being the electrical resistance of the heart's conductive pathways, the governing equation for heart's conductive operations is obtained from Ohm's Law. The value of R and V for the system were determined to be 100 Ω and 2.8 V. The component $H(s)$ represents the feedback gain, which was set to 1 to keep the output signal unaltered as it is fed back to the system.

$$G_p(s) = \frac{8}{s+8} \quad (1)$$

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

$$G_c(s) = K_c\left(1 + \tau_D s + \frac{1}{\tau_I s}\right) \quad (3)$$

$$I(s) = \frac{V}{R} \quad (4)$$

The transfer function of the pacemaker is that of a first order system with $\tau = 1/8$ and a steady- state gain of $K_{SS} = 1/8$. The pacemaker itself acts as a low-pass filter, preventing high frequency signals from being transmitted to the patient's heart.

PID Controller

The PID controller parameters are altered to obtain a desired controller response. Altering the parameters affects the rise tie, overshoot, oscillations, offset and the settling time. The PID controller should be tuned so that the following objectives are satisfied:

1) The pacemaker is driven so as to pace the heart at the desired rate in a short amount of time once the system is initiated.

2) The set point value should be reached without oscillations or overshoot.

To satisfy the first objective, the rise time and settling time have to be decreased. Clearly, an oscillating response or a response with a high overshoot is not desired for which the PID controller is tuned accordingly. The proportional and the integral control help decrease the rise time, the integral control eliminates the offset from the set point while the derivative control decreases the overshoot and the settling time of the response. MATLAB's PID Controller tuning tool was used to satisfy the purpose.

Accelerometer

The accelerometer's internal components can be expressed as a spring-mass-damper seismic structure with a strain gauge to convert a physical movement into a voltage. Such a system is depicted in Figure 3, where k is the spring constant, m is the mass, b is the damping coefficient, x is the position of the mass, and V_0 is the output voltage of the strain gauge.

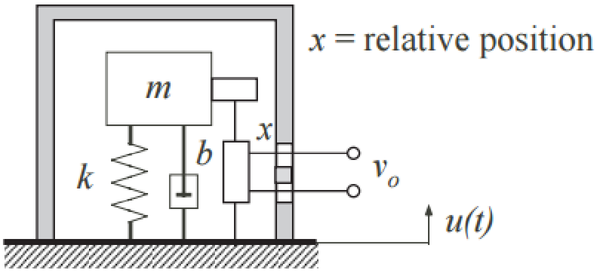

Figure 3

From Newton's Laws, a differential equation can be derived, and transformed into the s-domain to obtain the transfer function of the accelerometer. The equations and the transfer functions obtained from Laplace Transform are as follows:

$$\ddot{x} + 2\zeta\omega_n\dot{x} + \omega_n^2 x = \ddot{u} \qquad (5)$$

$$\frac{X}{\ddot{U}} = \frac{1}{\frac{1}{\omega_n}s^2 + \frac{2\zeta s}{\omega_n} + 1} \qquad (6)$$

where ω_n is the natural frequency of the system and ζ is the damping coefficient. The time constant τ could also be used to model the system, given the relationship $\tau = 1/\omega_n$.

$$G_{Acc}(s) = \frac{V_0}{\ddot{U}} = \frac{S_x}{\frac{1}{\omega_n^2}s^2 + \frac{2\zeta s}{\omega_n} + 1} \qquad (7)$$

Equation (7) shows that an accelerometer acts as a second order system, with a system damping coefficient $\zeta = b/2\ km$ and a natural frequency $\omega_n = k/m$, which can be tuned by selecting appropriate values for the mass, spring constant and damping coefficient. The accelerometer should exhibit a perfectly damped response so that changes in motion can be measured accurately. The value of ζ should be slightly less than 1 because values much smaller than 1 would mean underdamped response leading to oscillations while a value much greater than 1 would mean over damped response meaning that the responses would not be registered fast enough with the change in motion. The value of ω_n is chosen to be 0.5 so that any signals with frequencies higher than 2 rad/sec will be attenuated. This is done in order to output a set increase in heart rate for a dynamic signal as in the case when a person goes on a run. Having set the sensitivity S_x of the accelerometer to 60 would mean that the maximum heart rate at which the pacemaker would drive the heart would be 120 bpm.

From the closed loop system, the dependence of the final response $Y(s)$ on the set point $SP(s)$ and the physical activity input $U(s)$ are as follows:

$$Y(s) = \frac{G_P(s)\,G_C(s)\,G_H(s)\,I(s)}{1 + G_P(s)\,G_C(s)\,G_H(s)\,I(s)}\,SP(s) + \frac{G_P(s)\,G_C(s)\,G_H(s)\,I(s)\,G_{Acc}(s)}{1 + G_P(s)\,G_C(s)\,G_H(s)\,I(s)}\,U(s)$$

SIMULATION RESULTS

To test the Simulink model for the pacemaker-heart system, three different load signals were used. For all the load signals, the set point was set to 60 bpm. The load inputs that were used were a discrete input with a pulse duration of 0.5 seconds, a unit step input and sinusoidal waves of varying frequencies. The time delay is used to separate the response of the system when the pacemaker is on from the response to a system disturbance.

A. *Discrete Impulse Input*

This input load was used to model a scenario in which a person stands up, and the heart rate has to increase to account for an increase in pressure resulting from the motion of standing up. If the heart rate does not increase, the increase in pressure can decrease the flow of blood to the brain and make them faint. Figure 4 shows the response of a discrete step impulse with a time delay of 6 seconds. It is evident how the accelerometer's response is added to the overall system response.

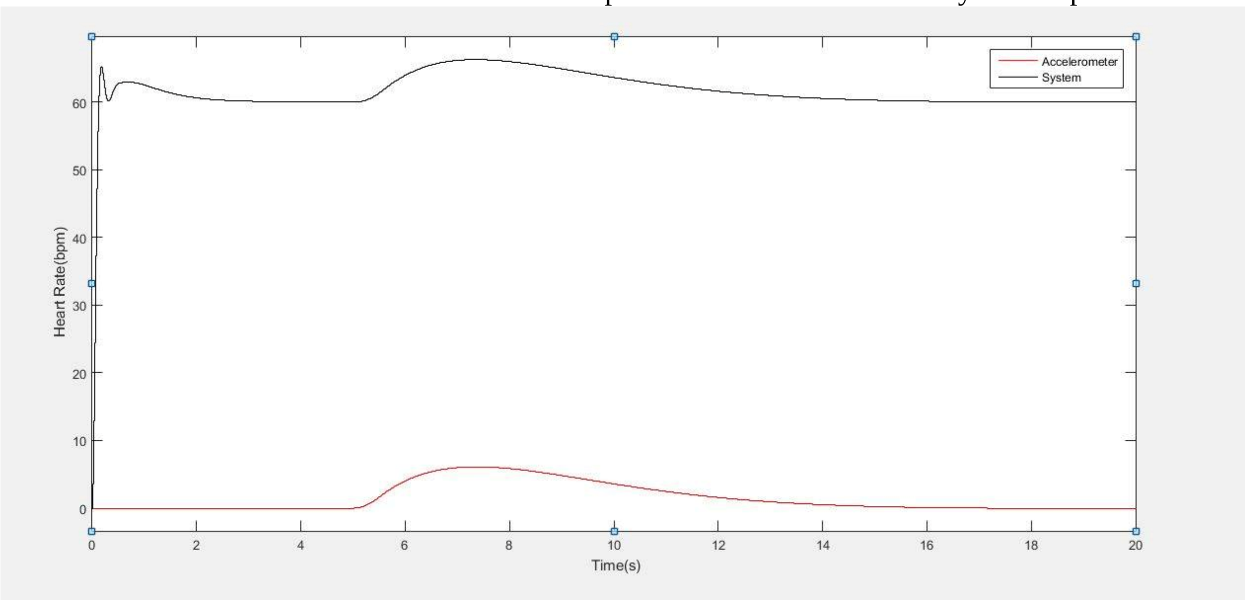

Figure 4

B. Unit Step Input

A unit step input was used to model a scenario in which a person with a pacemaker is undergoing a constant physical exertion that results in constant changes in motion. If a person goes on a run, the accelerometer would register constant changes in motion. As a result, the pacemaker would drive the heart at a higher rate to ensure proper supply of oxygenated blood throughout the body without which the body would not be able to handle the prolonged physical exertion. The sensitivity S_x was chosen to be 60 so that the maximum heart rate during prolonged physical exertion would be 120 bpm.

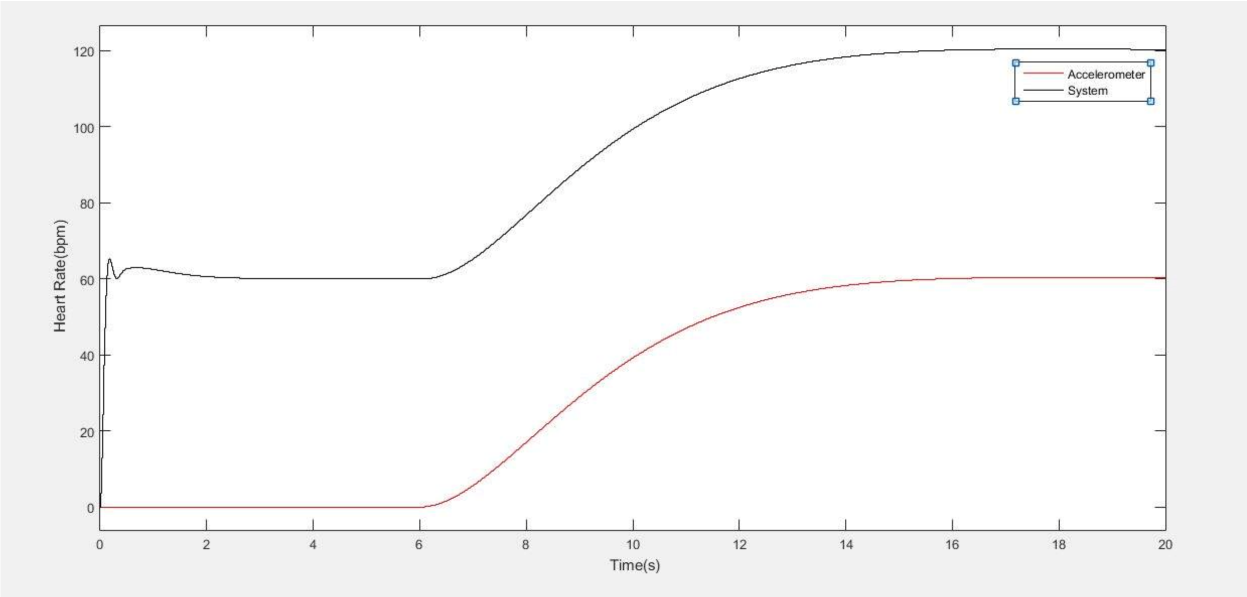

Figure 5

C. Sinusoidal Dynamic Wave Input

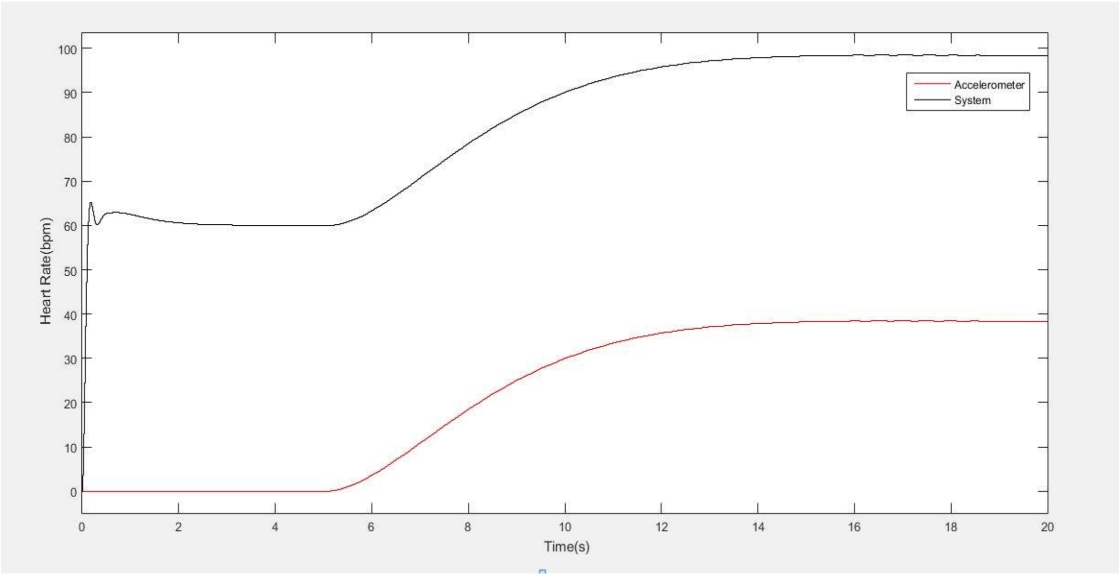

Figure 6

The accelerometer is unlikely to respond to the constant change in motion for a prolonged time, and so the system was tested for a dynamic sinusoidal input of different frequencies. The accelerometer is expected to increase the heart rate for motion detected in positive or negative direction. Figure 6 shows response of the system to a sinusoidal wave input of frequency 1 Hz, which is modelled for the movement of a person as he runs. As the cutoff frequency removed the dynamic response of the signal, the heart rate was constant which was what it was designed to do.

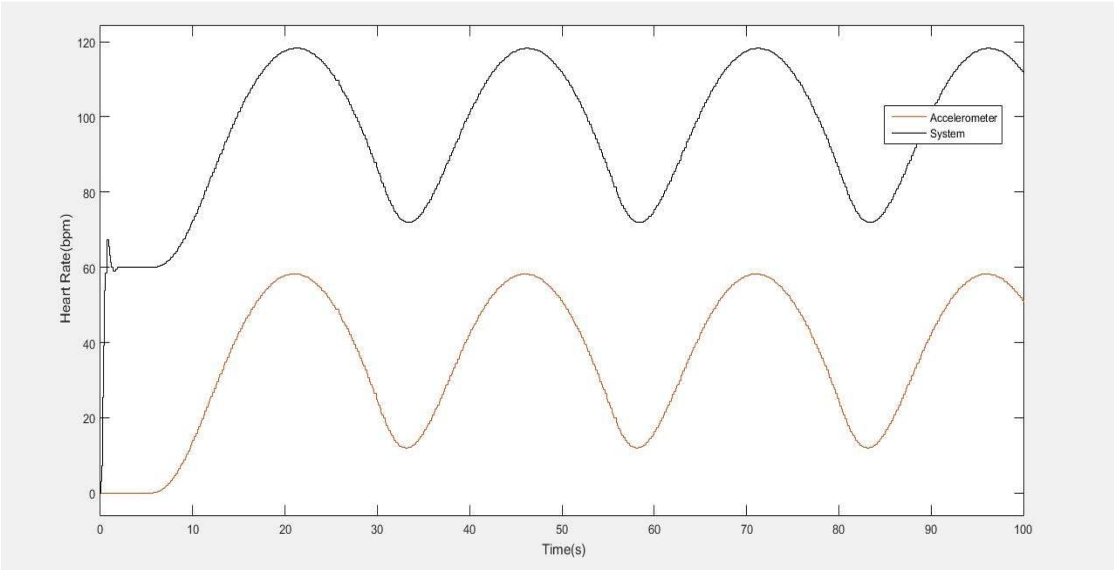

Figure 7

Figure 7 shows the system's response to a dynamic signal of frequency 0.02 Hz which is modelled for a person sitting down and standing up several times. Since the frequency is less than the cut off frequency, the signal was not attenuated.

D. PID Controller Tuning

Using MATLAB's PID Controlled Tuning tool, the following parameters for the PID controller and the system response were obtained.

	Tuned	Block
P	63.2056	63.2056
I	68.4509	68.4509
D	11.8097	11.8097
N	1808.4401	1808.4401

Performance and Robustness

	Tuned	Block
Rise time	0.085 seconds	0.085 seconds
Settling time	1.56 seconds	1.56 seconds
Overshoot	8.74 %	8.74 %
Peak	1.09	1.09
Gain margin	39.6 dB @ 206 rad/s	39.6 dB @ 206 rad/s
Phase margin	60 deg @ 15.8 rad/s	60 deg @ 15.8 rad/s
Closed-loop stability	Stable	Stable

E. Stability Analysis

The stability analysis for the system was performed using different methods such as Root Locus Diagram, Nyquist Plot, Bode Plot and Routh's Array Method. All the methods gave nearly the same value for critical value of controller gain to be 127. The Nyquist plot, root locus diagram and the Bode plot results have been depicted in the figures.

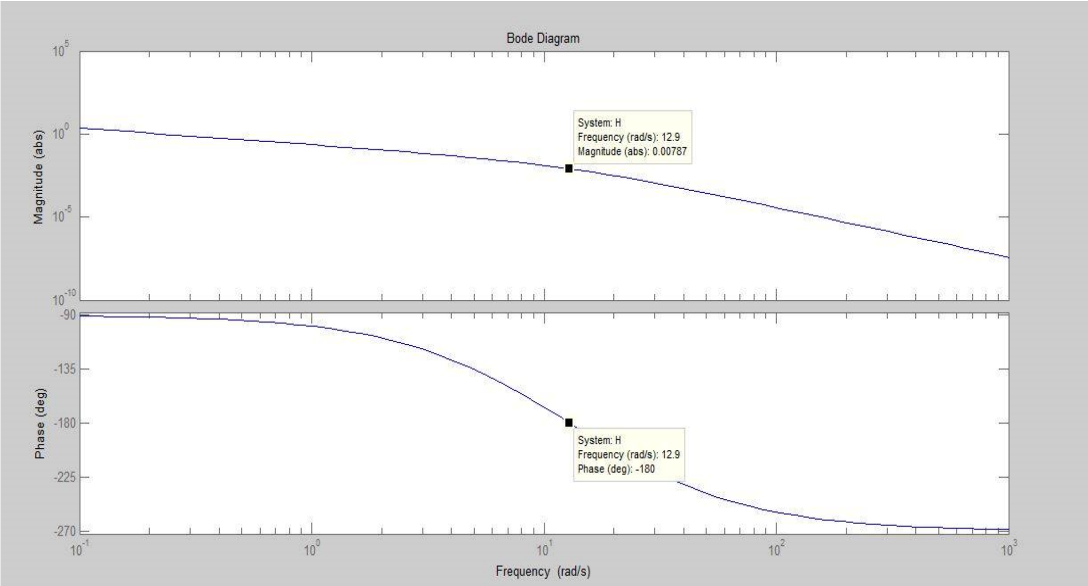

Figure 8

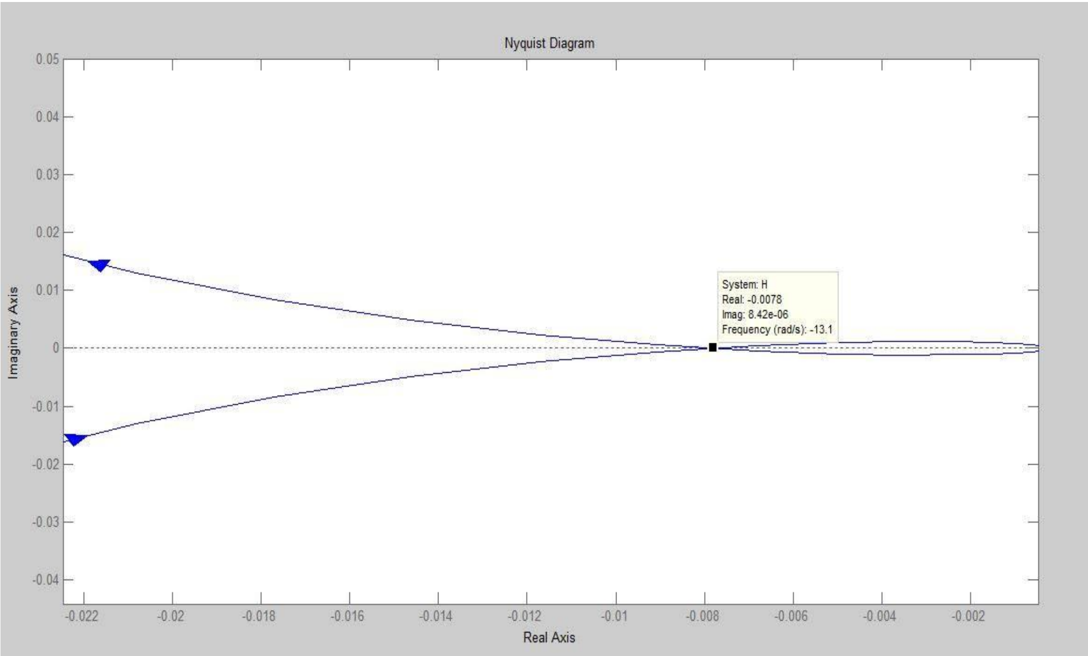

Figure 9

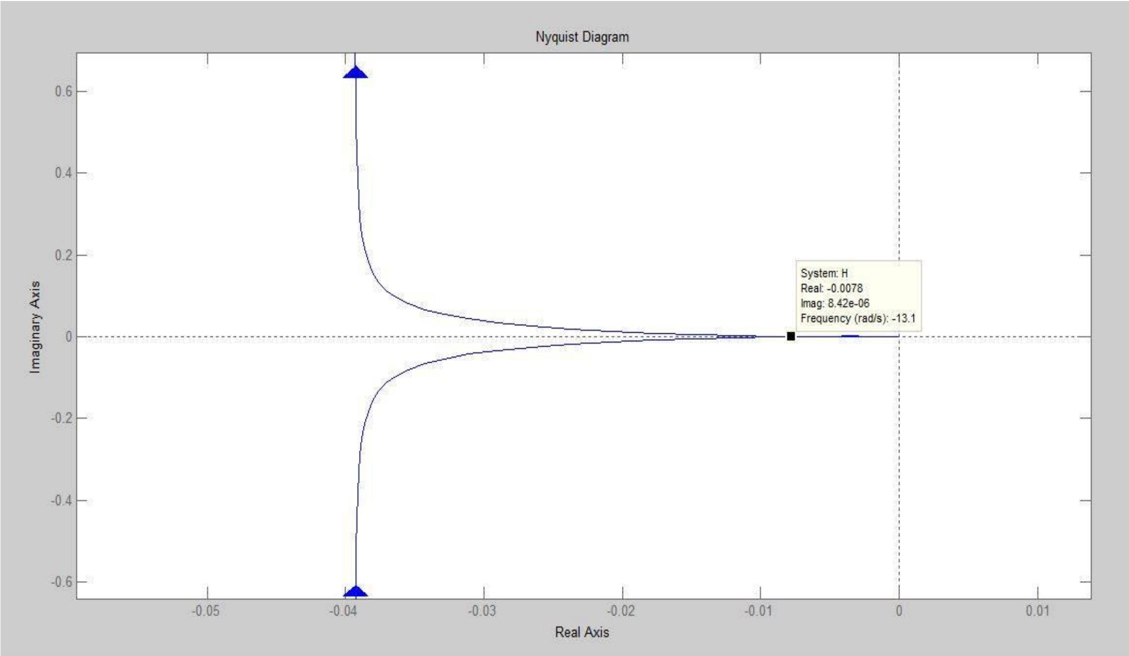

Figure 10

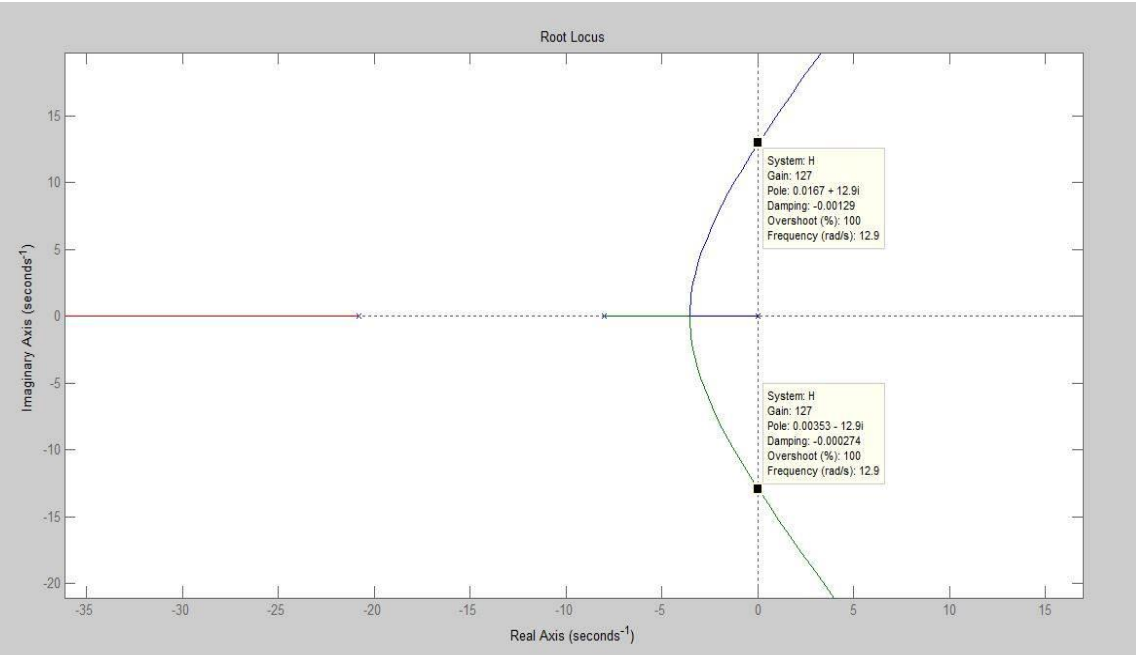

Figure 11

DISCUSSION

The above discussed model was used to study the effect and need of control systems in physiological processes such as a pacemaker-heart system. The model was simplified using some assumptions which offers a few limitations due to the simplification of the model. Some of the limitations are that heart has been assumed to perform under ideal conditions without different modalities such as contractility and ventilation patterns which also affect the heart rate. Only physical motions detected by an accelerometer were used for the study. The pacemaker was modelled as a set of transfer functions neglecting the complexity of the device. The current and resistance of the heart changes due to change in concentration of intra-cellular and extra-cellular ions. The heart has been modelled as a single chamber meaning that the frequencies of other chambers have been ignored.

The model used in the report does not truly account for the physiological aspects of the pacemaker-heart system and the simplifications used ignore quite a few key factors which also affect the heart rate, but the model offers a good insight into the use of control systems, controller tuning, stability criteria and mathematical simulation of processes. So, the purpose of the report which was to learn about integration of control systems in different processes was justified.