3K04 Assignment 1 Part 1 & 3

Pacemaker Simulink Documentation

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1 Atrium Implementation

1.1 Introduction

In the following section of this document, the implementation of the pacemaker controlling the atrium (upper chambers of the heart) will be expressed in detail. The design of modes AOO and AAI [2] will be described through design decisions, state flow, testing, and future improvements to be made in the controlling of the atrium.

1.2 AOO Overview & Design

The focus for the AOO mode in the pacemaker is to generate a pulse that is autonomous from the natural heartbeat. In doing so, the pacemaker will send signals to the atrium to contract the muscles at a desired rate without sensing the patient's natural heartbeat. Therefore, this mode may be used in the case that a person's heart does not beat on its own at all in which the pacemaker will completely take over the pumping of blood.

From observing the table of bradycardia operating modes and the programmable parameters for the AOO mode [2], a design was developed to mimic a pacemaker. Using Simulink, a model was built to program and operate the pacemaker in the AOO mode. Within this model, several variables were used to control the beats per minute (BPM), corresponding circuits [1], states, voltages, and pulse width modulation (PWM). Two states were used in the system in which one was used for charging the main capacitor (C22) and discharging the output capacitor (C21) [1], while the other state was used for pacing the heart. An input ranging from 0V to 5V was given to the amplitude of the pulse where a PWM signal was produced at a desired frequency and duty cycle. The pulse width as well as the lower rate limit (LRL) were inputs that controlled the timing between the two states along with LRL directly controlling the BPM.

According to section 3.2 in *Pacemaker Microcontroller Shield* [1], there are 3 steps when it comes to pacing the heart: charging the C22 capacitor, pacing the heart, and discharging the C21 capacitor. The decision was made to combine the first and last steps into one state so that the system would not be wasting any time in a state just for discharging.

One thing that is likely to change with the pacemaker is the implementation of both AOO and AAI operating in the same Simulink system. This could be implemented by simply including another input variable that would switch the modes based on an inputted value. It was decided against this design decision because it would require one complex system, versus two fairly simple systems. The states are not able to be shared between the different modes because the time at which the system remains in each state is different with each mode. However, combining both systems is a possibility that will likely come to fruition to have a complete system with all modes.

1.3 AAI Overview & Design

The AAI mode is implemented with functionalities of pacing the atrium while sensing the patient's natural heartbeat. This mode is helpful when a patient's heartbeat is irregular. For example, if a patient's resting heart rate is 70 BPM but their heart only beats at 35 BPM, then the pacemaker will account for the irregularities and aid the heartbeat to its desired rate. As long as the patient's heart beats above the set LRL, the pacemaker will not provide any pacing of its own.

Similar to mode AOO, a Simulink model was created to implement AAI into the pacemaker. Most of the same inputs and outputs were used as in AOO with the difference of inputs to detect the patient's natural heartbeat. The amplitude will still control the voltage allowed into the circuit and the duty cycle of the PWM will control the intensity of the average voltage. The allowable ranges of each parameter value can be found in *PACEMAKER System Requirements* [2]. The system has two main states: one for charging and discharging, and one for pacing the atrium. There are waiting states that incorporate the use of an atrial refractory period (ARP) [2]. The inclusion of an ARP is necessary to the design in the AAI mode as it is a programmed time interval following an atrial event during which pacing will not be inhibited. The system will change states based on the LRL, pulse width, and depending on if a natural heartbeat is sensed. If there is a natural heartbeat, the pacemaker will remain in the charging state where C22 will remain charged until a natural heartbeat is no longer sensed.

The decision was made to incorporate only two states because as long as there is a natural regular heartbeat, the system can remain in an idle state of charging the C22 capacitor. Only until there is an irregular/no heartbeat, will the system inhibit a pace to the heart in which it will do so at the desired rate.

Something likely to change is the implementation of AOO and AAI in the same system. As discussed in section 1.2 above, the decision to have the different modes be in different systems was made to simplify the solutions. This will change in future iterations of the pacemaker system where all modes will be controlled under one coherent system.

1.4 Variables

1.4.1 Inputs

Most of the input variables are shared between both the AOO and AAI modes. Table 1 displays all input variables used within the atrium modes.

* = inputs only in mode AAI

NAME	DESCRIPTION	ALLOWED VALUES	TYPE/UNIT
Amplitude	Inputs a voltage for the PWM signal from 0-5V	0 - 5	V
Pulse Width	The desired width of the paced signal	0.1 - 1.9	msec
Lower Rate Limit (LRL)	The number of generated paced pulses delivered to the atrium	30 - 175	PPM
Upper Rate Limit (URL)	The maximum rate at which it will sense events	50 - 175	PPM

SENSED/ATR_CMP_DETECT*	Determines if there is a natural heartbeat	true/false	boolean
Atrial Refractory period (ARP)*	Time interval in which no sensing/pacing occurs after a sensed ventricular pace	150 - 500	msec

Table 1: Input variables of modes AOO and AAI

1.4.2 Outputs

Most of the output variables are shared between both AOO and AAI modes. Table 2 displays the output variables in the atrium systems.

* = outputs only in mode AAI

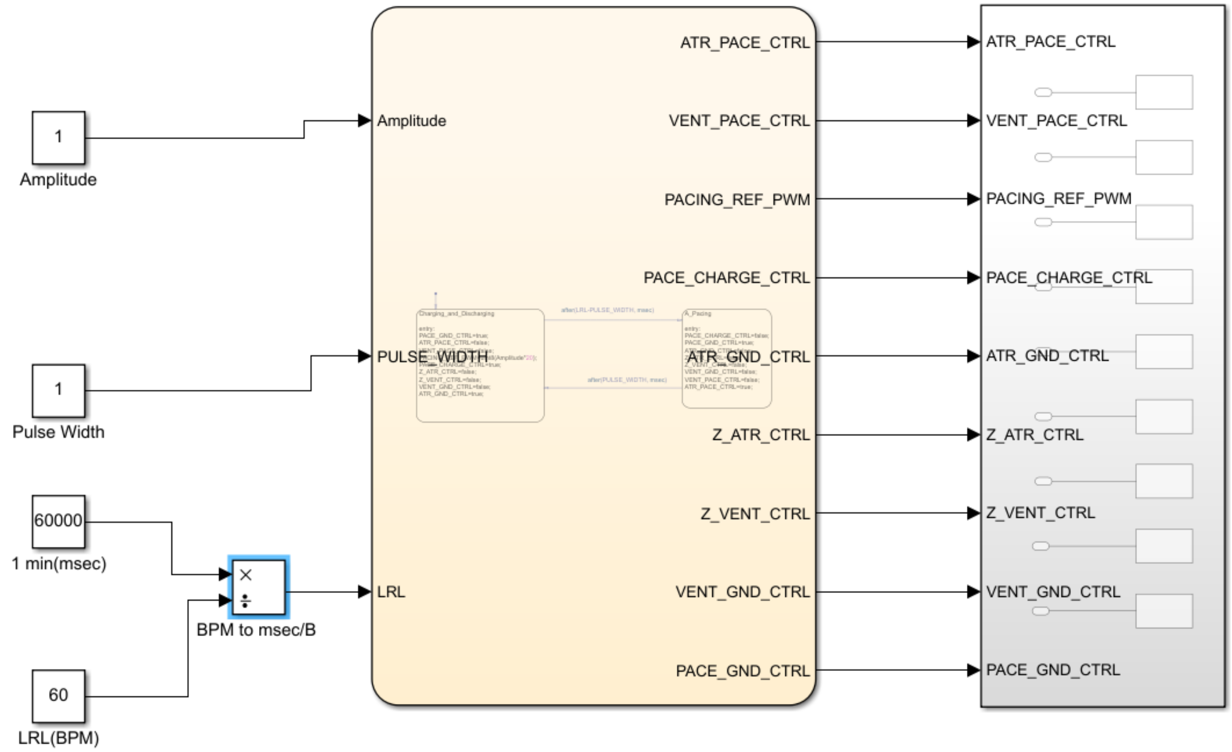
NAME	DESCRIPTION	ALLOWED VALUES	TYPE/UNIT
ATR_PACE_CTRL	Enables pacing to atrium	true/false	boolean
VENT_PACE_CTRL	Enables pacing to ventricle	true/false	boolean
PACING_REF_PWM	Signal that charges the C22 capacitor to then be sent to the heart	0 - 100	Duty Cycle (%)
PACE_CHARGE_CTRL	Allows the C22 capacitor to be charged	true/false	boolean
ATR_GND_CTRL	Discharges C21 in the atrium to avoid charge build up in the heart	true/false	boolean
Z_ATR_CTRL	Used for analysis on the impedance in the atrium	true/false	boolean
Z_VENT_CTRL	Used for analysis on the impedance in the ventricle	true/false	boolean
VENT_GND_CTRL	Discharges C21 in the ventricle to avoid charge build up in the heart	true/false	boolean
ATR_CMP_REF_PWM*	Establishes the minimum threshold for atrium action potential to be sensed	0 - 100	Duty Cycle (%)

Table 2: Output variables of modes AOO and AAI

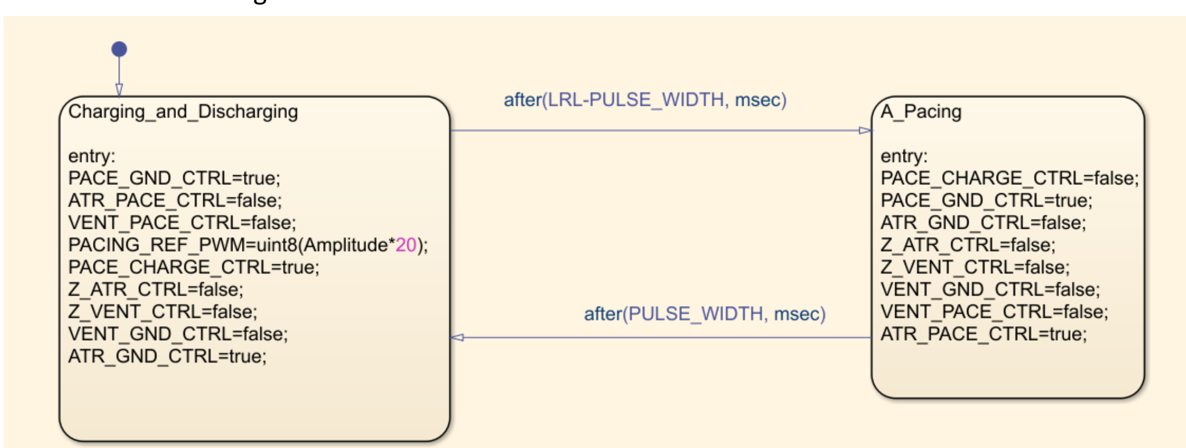
1.5 Atrium Simulink Design

1.5.1 AOO mode

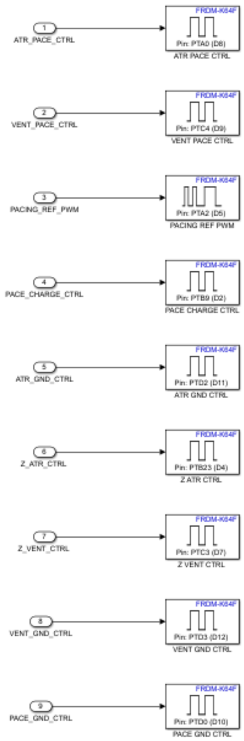
1.5.1.1 System Overview



1.5.1.2 State flow diagram

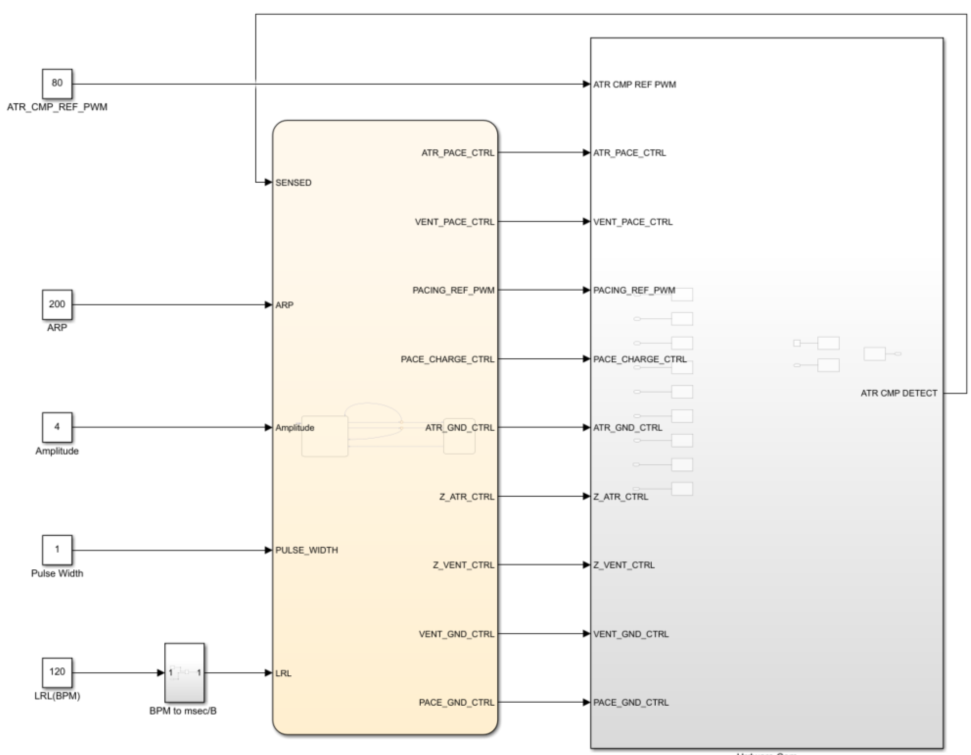


1.5.1.3 Subsystem

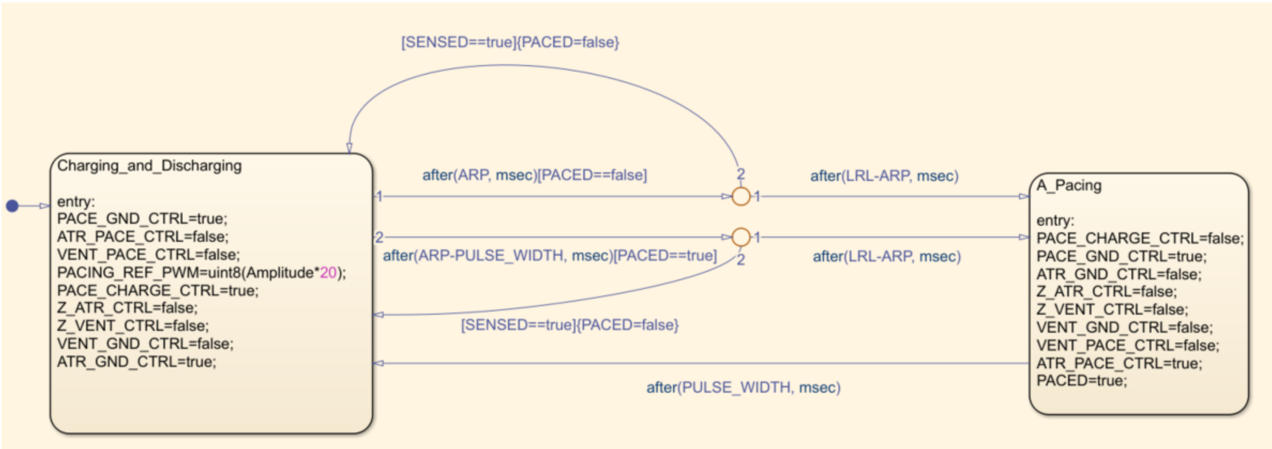


1.5.2 AAI mode

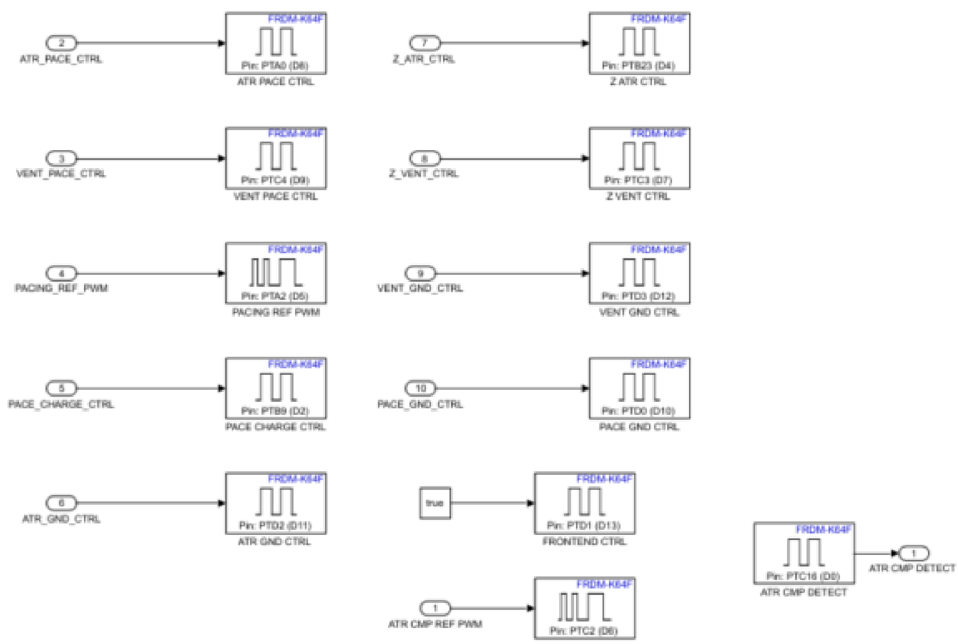
1.5.1.1 System Overview



1.5.1.2 State flow diagram



1.5.1.3 Subsystem



1.6 Atrium Testing

1.6.1 AOO Testing

Pacemaker inputs	Heartview inputs	Expected output	Test result (PASS/FAIL)
Amplitude = 1V Pulse width = 1ms BPM = 60	NA	Paced heartbeat at 1 beat/second with the max amplitude at 1V	PASS
Amplitude = 3V Pulse width = 1ms	NA	Paced heartbeat at 90BPM with the max	PASS

BPM = 90		amplitude at 3V	
Amplitude = 3V Pulse width = 5ms BPM = 90	NA	Paced heartbeat at 90BPM with wider signal pulse	PASS
Amplitude = 1V Pulse width = 1ms BPM = 120	Pulse width = 1ms BPM = 60	Natural heartbeat and faster paced heartbeat; no sensing	PASS
Amplitude = 3V Pulse width = 100ms BPM = 90	Pulse width = 1ms BPM = 90	Large delay between paced voltage and recovery voltage	PASS
Amplitude = 10V Pulse width = 5ms BPM = 60	Pulse width = 1ms BPM = 120	No pacing since amplitude is out of bounds; natural beats	PASS

1.6.2 AAI Testing

Pacemaker inputs	Heartview inputs	Expected output	Test result (PASS/FAIL)
Amplitude = 1V Pulse width = 1ms BPM = 60 ARP = 0	NA	Normal paced heartbeat at 1 beat/second with the max amplitude at 1V	PASS
Amplitude = 3V Pulse width = 1ms BPM = 120 ARP = 0	Pulse width = 1ms BPM = 60	Pacing to help the heart beat at 120 BPM (pace every other natural heartbeat)	PASS
Amplitude = 3V Pulse width = 1ms BPM = 90 ARP = 0	Pulse width = 1ms BPM = 90	No pacing since heart is beating fast enough	PASS
Amplitude = 1V Pulse width = 1ms BPM = 60 ARP = 150	Pulse width = 1ms BPM = 90	No pacing since heart is beating fast enough	PASS
Amplitude = 3V Pulse width = 1ms BPM = 90 ARP = 200	Pulse width = 1ms BPM = 90	Pacing with the waiting ARP implementation	PASS
Amplitude = 3V Pulse width = 5ms	Pulse width = 1ms BPM = 30	Pacing with the waiting ARP implementation	PASS

BPM = 90 ARP = 200			

2 Ventricle Implementation

2.1 Introduction

This section of the pacemaker documentation is focused on controlling the ventricle (lower chambers of the heart) with the ventricular modes VOO and VVI [2]. The current design, state flow, future design, and testing methods will be discussed throughout this section.

2.2 VOO Overview & Design

Similar to mode AOO (in section 1), the focus for the VOO mode in the pacemaker is to generate a pulse that is autonomous from the natural heartbeat. In doing so, the pacemaker will send signals to the ventricle to contract the muscles at a desired rate without sensing the patient's natural heartbeat. Therefore, this mode may be used in the case that a person's heart does not beat on its own at all in which the pacemaker will completely take over the pumping of blood.

From observing the table of bradycardia operating modes and the programmable parameters for the VOO mode [2], a design was developed to mimic a pacemaker. Using Simulink, a model was built to program and operate the pacemaker in the VOO mode. Within this model, several variables were used to control the beats per minute (BPM), corresponding circuits [1], states, voltages, and pulse width modulation (PWM). Two states were used in the system in which one was used for charging the main capacitor (C22) and discharging the output capacitor (C21) [1], while the other state was used for pacing the heart. An input ranging from 0V to 5V was given to the amplitude of the pulse where a PWM signal was produced at a desired frequency and duty cycle. The pulse width as well as the lower rate limit (LRL) were inputs that controlled the timing between the two states along with LRL directly controlling the BPM.

According to section 3.2 in *Pacemaker Microcontroller Shield* [1], there are 3 steps when it comes to pacing the heart: charging the C22 capacitor, pacing the heart, and discharging the C21 capacitor. The decision was made to combine the first and last steps into one state so that the system would not be wasting any time in a state just for discharging.

One thing that is likely to change with the pacemaker is the implementation of both VOO and VVI operating in the same Simulink system. This could be implemented by simply including another input variable that would switch the modes based on an inputted value. It was decided against this design decision because it would require one complex system, versus two fairly simple systems. The states are not able to be shared between the different modes because the time at which the system remains in each state is different with each mode. However, combining both systems is a possibility that will likely come to fruition to have a complete system with all modes.

2.3 VVI Overview & Design

The VVI mode is implemented with functionalities of pacing the ventricle while sensing the patient's natural heartbeat. This mode is helpful when a patient's heartbeat is irregular.

Similar to mode VOO, a Simulink model was created to implement VVI into the pacemaker. Most of the same inputs and outputs were used as in VOO with the difference of inputs to detect the patient's natural heartbeat. The amplitude will still control the voltage allowed into the circuit and the duty cycle of the PWM will control the intensity of the average voltage. The allowable ranges of each parameter value can be found in *PACEMAKER System Requirements* [2]. The system has two main states: one for charging and discharging, and one for pacing the ventricle. There are waiting states that incorporate the use of a ventricular refractory period (VRP) [2]. The inclusion of a VRP is necessary to the design in the VVI mode as it is a programmed time interval following an ventricular event during which pacing will not be inhibited. The system will change states based on the LRL, pulse width, and depending on if a natural heartbeat is sensed. If there is a natural heartbeat, the pacemaker will remain in the charging state where C22 will remain charged until a natural heartbeat is no longer sensed.

The decision was made to incorporate only two main states because as long as there is a natural regular heartbeat, the system can remain in an idle state of charging the C22 capacitor. Only until there is an irregular/no heartbeat, will the system inhibit a pace to the heart in which it will do so at the desired rate.

Something likely to change is the implementation of VOO and VVI in the same system. As discussed in section 2.2 above, the decision to have the different modes be in different systems was made to simplify the solutions. This will change in future iterations of the pacemaker system where all modes will be controlled under one coherent system.

2.4 Variables

2.4.1 Inputs

Most of the input variables are shared between both the VOO and VVI modes. Table 3 displays all input variables used within the ventricle modes.

* = inputs only in mode VVI

NAME	DESCRIPTION	ALLOWED VALUES	TYPE/UNIT
Amplitude	Inputs a voltage for the PWM signal from 0-5V	0 - 5	V
Pulse Width	The desired width of the paced signal	0.1 - 1.9	msec
Lower Rate Limit (LRL)	The number of generated paced pulses delivered to the ventricle	30 - 175	PPM

Upper Rate Limit (URL)	The maximum rate at which it will sense events	50 - 175	PPM
SENSED/ATR_CMP_DETECT*	Determines if there is a natural heartbeat	true/false	boolean
Ventricular Refractory period (VRP)*	Time interval in which no sensing/pacing occurs after a sensed ventricular pace	150 - 500	msec

Table 3: Input variables of modes VOO and VVI

2.4.2 Outputs

Most of the output variables are shared between both VOO and VVI modes. Table 2 displays the output variables in the ventricle systems.

* = outputs only in mode VVI

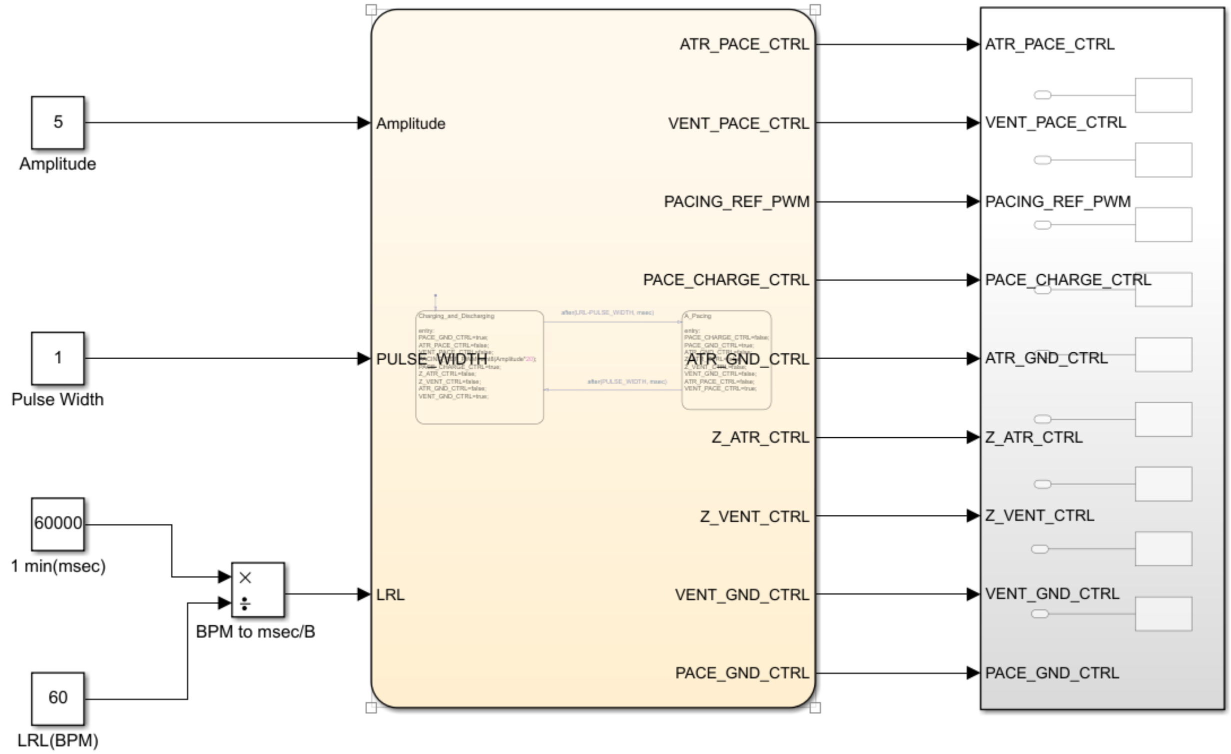
NAME	DESCRIPTION	ALLOWED VALUES	TYPE/UNIT
ATR_PACE_CTRL	Enables pacing to atrium	true/false	boolean
VENT_PACE_CTRL	Enables pacing to ventricle	true/false	boolean
PACING_REF_PWM	Signal that charges the C22 capacitor to then be sent to the heart	0 - 100	Duty Cycle (%)
PACE_CHARGE_CTRL	Allows the C22 capacitor to be charged	true/false	boolean
ATR_GND_CTRL	Discharges C21 in the atrium to avoid charge build up in the heart	true/false	boolean
Z_ATR_CTRL	Used for analysis on the impedance in the atrium	true/false	boolean
Z_VENT_CTRL	Used for analysis on the impedance in the ventricle	true/false	boolean
VENT_GND_CTRL	Discharges C21 in the ventricle to avoid charge build up in the heart	true/false	boolean
VENT_CMP_REF_PWM*	Establishes the minimum threshold for atrium action potential to be sensed	0 - 100	Duty Cycle (%)

Table 4: Output variables of modes VOO and VVI

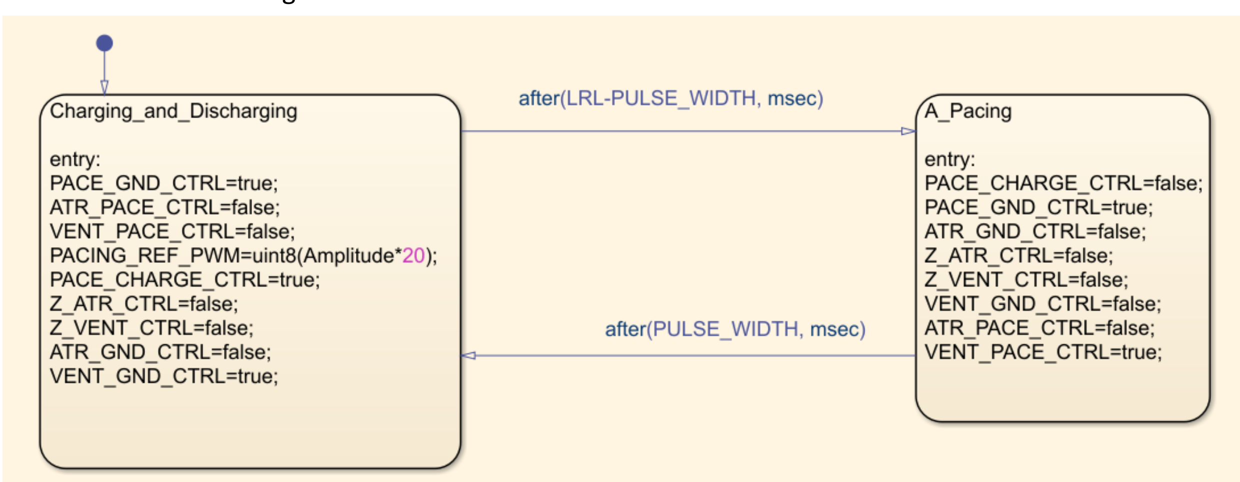
2.5 Ventricle Simulink Design

2.5.1 VOO mode

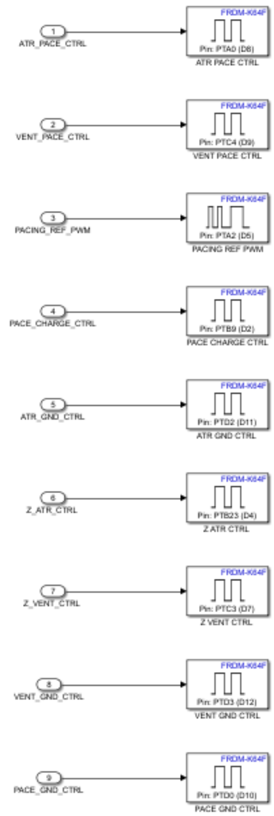
2.5.1.1 System Overview



2.5.1.2 State flow diagram

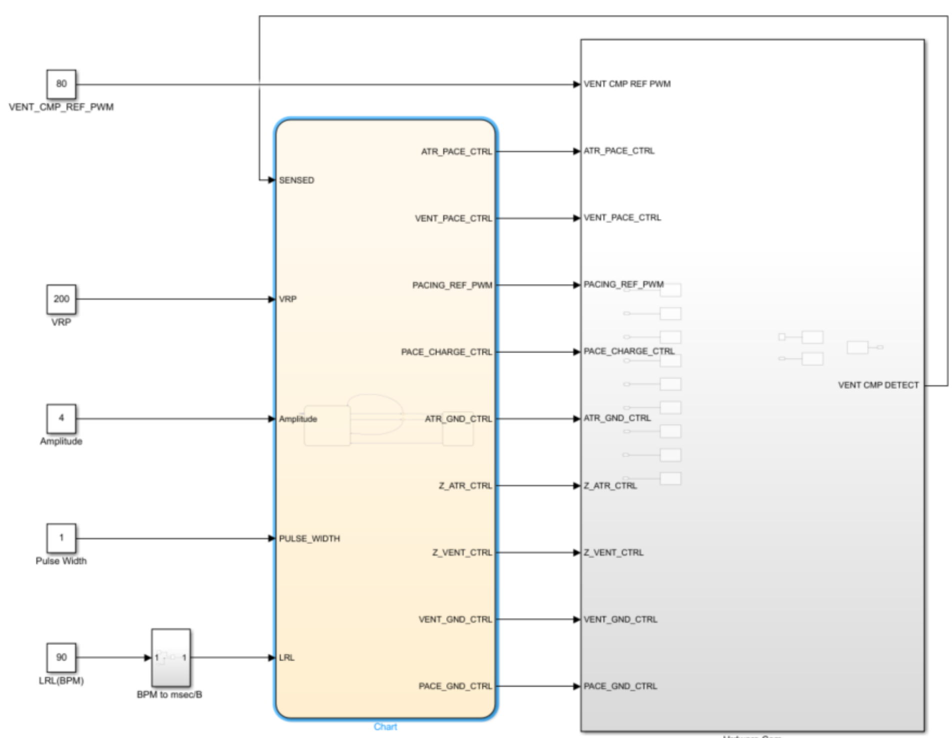


2.5.1.3 Subsystem

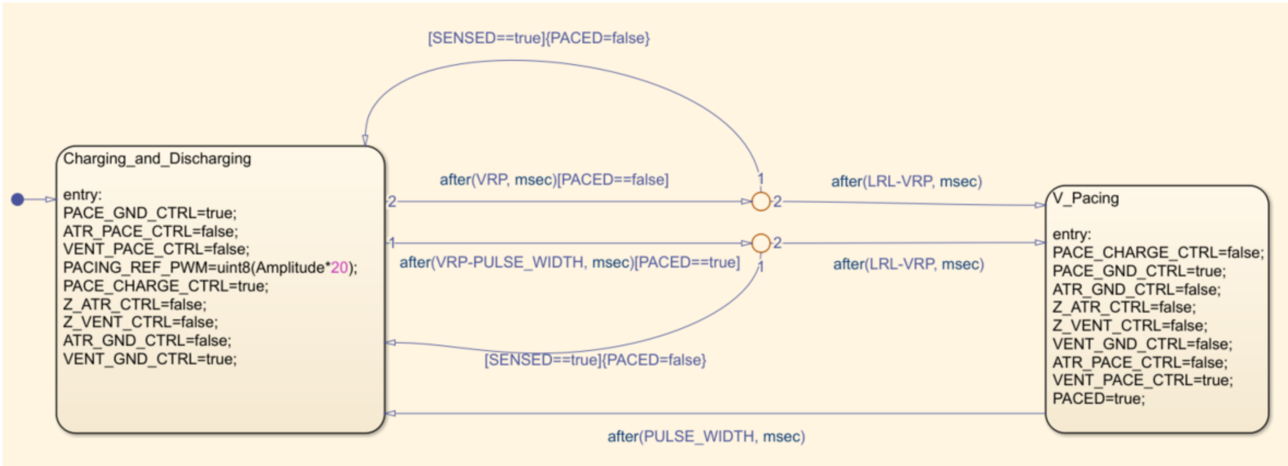


2.5.2 VVI mode

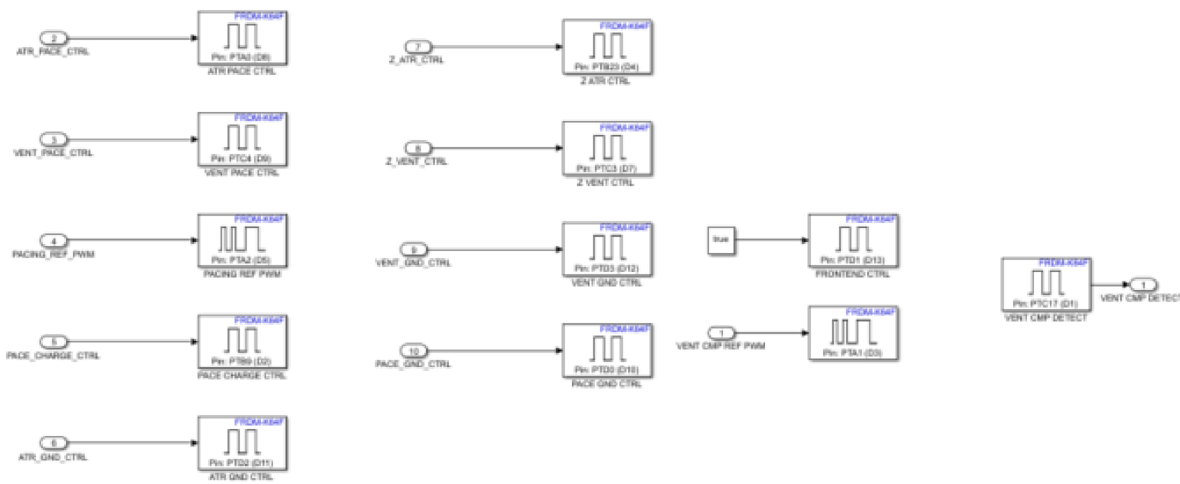
2.5.2.1 System Overview



2.5.2.2 State flow diagram



2.5.2.3 Subsystem



2.6 Ventricle Testing

2.6.1 VOO Testing

Pacemaker inputs	Heartview inputs	Expected output	Test result (PASS/FAIL)
Amplitude = 1V Pulse width = 1ms BPM = 60	NA	Paced heartbeat at 1 beat/second with the max amplitude at 1V	PASS
Amplitude = 3V Pulse width = 1ms BPM = 90	NA	Paced heartbeat at 90BPM with the max amplitude at 3V	PASS
Amplitude = 3V Pulse width = 5ms	NA	Paced heartbeat at 90BPM with wider	PASS

BPM = 90		signal pulse	
Amplitude = 1V Pulse width = 1ms BPM = 120	Pulse width = 1ms BPM = 60	Natural heartbeat and faster paced heartbeat; no sensing	PASS
Amplitude = 3V Pulse width = 100ms BPM = 90	Pulse width = 1ms BPM = 90	Large delay between paced voltage and recovery voltage	PASS
Amplitude = 10V Pulse width = 5ms BPM = 60	Pulse width = 1ms BPM = 120	No pacing since amplitude is out of bounds; natural beats	PASS

2.6.2 VVI Testing

Pacemaker inputs	Heartview inputs	Expected output	Test result (PASS/FAIL)
Amplitude = 1V Pulse width = 1ms BPM = 60 VRP = 0	NA	Normal paced heartbeat at 1 beat/second with the max amplitude at 1V	PASS
Amplitude = 3V Pulse width = 1ms BPM = 120 VRP = 0	Pulse width = 1ms BPM = 60	Pacing to help the heart beat at 120 BPM (pace every other natural heartbeat)	PASS
Amplitude = 3V Pulse width = 1ms BPM = 90 VRP = 0	Pulse width = 1ms BPM = 90	No pacing since heart is beating fast enough	PASS
Amplitude = 1V Pulse width = 1ms BPM = 60 VRP = 150	Pulse width = 1ms BPM = 90	No pacing since heart is beating fast enough	PASS
Amplitude = 3V Pulse width = 1ms BPM = 90 VRP = 200	Pulse width = 1ms BPM = 90	Pacing with the waiting VRP implementation	PASS
Amplitude = 3V Pulse width = 5ms BPM = 90 VRP = 200	Pulse width = 1ms BPM = 30	Pacing with the waiting VRP implementation	PASS

3 Improvements

The current version of the pacemaker has much to improve upon as there are only a few functional modes. Future changes will include various modes to better accommodate for more patients such as: DOO, AOOR, VOOR, AAIR, VVIR, DOOR, and DDDR [2]. With the addition of new and more complex modes, new input and output variables will be a necessary addition to the overall design of the pacemaker. Including an onboard push button to pace the heart is also a possible addition to the current pacemaker design for better user experience. Generating a serial connection between the device controller monitor (DCM) [2] and the Simulink design will be included in the future so that changing modes and inputs can be easily done by anyone with authentication access to the DCM (ie. doctors). Another possible improvement will be the implementation of real-time electrograms so the patients and doctors always have access to the activity of the patient's heart signals.

4 Citations

[1]
G. Meyer, "Pacemaker Microcontroller Shield", *McMaster University*, November 2020.

[Accessed: September 30, 2021]
[2]
"PACEMAKER System Specification", *Boston Scientific*, January 3, 2007. [Accessed: September 30, 2021