McMaster University

SFWRENG 3K04 – Software Development

PACEMAKER SIMULINK

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Lab 1 Group 8

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2 Introduction

The following documentation gives a concise and general description tailored to the end-user, of the Simulink implementation of the SFWRENG 3K04 Pacemaker Project. The aim of this project is to construct a working pacemaker that acts and reacts to its environment accordingly, as a normal pacemaker would. This documentation will solely focus on the 10 implemented pacing/sensing modes (AOO, VOO, VVI, AAI, DOO, AOOR, VOOR, AAIR, VVIR, and DOOR).

To avoid any confusion, pacing refers to depolarization of the atria or ventricles. Sensing refers to detection of chamber signals. The VVI, AAI, VVIR and AAIR modes both provide sensing and pacing of the heart. VVI and VVIR are used for the ventricles, while AAI and AAIR are used for the Atrium. Those four modes act on an inhibited basis, meaning that the pacemaker is deactivated on a certain activity from the corresponding chamber. AOO, VOO, AOOR, VOOR, DOO and DOOR only pace (no sensing) the atrium and/or ventricle.

The AOO, VOO, AAI, VVI and DOO modes all provide pacing independent of the patient's activity, whereas the AOOR, VOOR, AAIR, VVIR and DOOR modes all use data from the onboard accelerometer to pace at an adaptive rate.

3 All Variables

3.1 Measured

Name	**Units/Type**	**Description**	**Range**
t	ms	Time since last pulse	–
ATR_SIGNAL	double	electrocardiogram measurement of atrial signal	0 – 1
VENT_SIGNAL	double	electrocardiogram measurement of ventricular signal	0 – 1
ATR_CMP_DETECT	boolean	Atrial signal voltage higher than threshold	{true, false}
VENT_CMP_DETECT	boolean	Ventricular signal voltage higher than threshold	{true, false}
accel	double x 3	Proper acceleration in g of pacemaker in local (x,y,z)	-4 – 4
Rx	uint8 x 17	UART in buffer	0 – 255
Status	uint8	Indicates whether UART buffer is full	{0, 32}

3.2 Parameters

Name	**Units/Type**	**Description**	**Range**
p_mode	–	Pacemaker operational mode	{AOO,VOO,AAI,VVI, DOO, AOOR, VOOR, AAIR, VVIR, DOOR}
p_lower_rate_limit	ppm	Lowest allowable heart rate	30 – 175 ± 8 ms

p_av_delay	ms	Delay between paced atrial and ventricular signals	70 – 300 ms ± 8 ms
p_atr_amplitude	V	Amplitude of pulse delivered to atrium	0 – 5 ± 12%
p_vent_amplitude	V	Amplitude of pulse delivered to ventricle	0 – 5 ± 12%
p_atr_sensitivity	V	Minimum voltage over which signal in atrium is classified as a pulse	0 – 5 ± 2%
p_vent_sensitivity	V	Minimum voltage over which signal in ventricle is classified as a pulse	0 – 5 ± 2%
p_atr_pulse_width	ms	Pulse width of atrial pace	1 – 30 ± 0.2 ms
p_vent_pulse_width	ms	Pulse width of ventricular pace	1 – 30 ± 0.2 ms
p_vrp	ms	Ventricular Refractory Period	150–500 ± 8 ms
p_arp	ms	Atrial Refractory Period	150–500 ± 8 ms
p_max_sensor_rate	ppm	Maximum sensor rate indicated by rate adaptivity	50 – 175 ± 4 ppm
p_activity_threshold	–	Minimum activity level for rate adaptivity	{V-Low, Low, Med-Low, Med, Med-High, High, V-high}
p_reaction_time	sec	Time required for pacing rate to rise from lower rate limit to max sensor rate	10 – 50 ± 3 sec
p_response_factor	–	Indicates response to activity levels above threshold	{true, false}
p_recovery_time	min	Maximum allowable pacing rate decrease	2 – 16 ± 30 sec

3.3 Controlled

Name	Units/Type	Description	Range
PACE_CHARGE_CTRL	boolean	PWM connected to primary capacitor	{true, false}
ATR_PACE_CTRL	boolean	Atrial ring connected to primary capacitor	{true, false}
VENT_PACE_CTRL	boolean	Ventricular ring connected to primary capacitor	{true, false}
ATR_GND_CTRL	boolean	Atrial ring connected to ground	{true, false}
VENT_GND_CTRL	boolean	Ventricular ring connected to ground	{true, false}
PACE_GND_CTRL	boolean	Atrial and Ventricular tip connected to blocking capacitor	{true, false}

Z_ATR_CTRL	boolean	Impedance circuit connected to atrial ring	{true, false}
Z_VENT_CTRL	boolean	Impedance circuit connected to ventricular ring	{true, false}
PACING_REF_PWM	%	Reference PWM for primary capacitor	0–100
ATR_CMP_REF_PWM	%	Reference PWM for atrial signal comparator	0–100
VENT_CMP_REF_PWM	%	Reference PWM for ventricular signal comparator	0–100
FRONTEND_CTRL	boolean	Sensing circuit connected to leads	{true, false}
Tx	uint8 x 16	UART out buffer	0 – 255

3.4 Internal

Name	Units/Type	Description	Range
h_atr_pulse_detected	boolean	Pulse detected in atrium	{true, false}
h_vent_pulse_detected	boolean	Pulse detected in ventricle	{true, false}
XOO_pace_start	boolean	AOO or VOO indicates pace	{true, false}
XXI_pace_start	boolean	AAI or VVI indicates pace	{true, false}
DOO_A_pace_start	boolean	DOO indicates atrial pace	{true, false}
DOO_V_pace_start	boolean	DOO indicates ventricular pace	{true, false}
DOO_AV_select	boolean	DOO indicates which chamber will be paced next	{true, false}
A_pace_start	boolean	Signal to pace atrium	{true, false}
V_pace_start	boolean	Signal to pace ventricle	{true, false}
AV_select	boolean	Selects which chamber will be paced next	{A, V}
sensor_rate	ppm	Rate adaptivity indicated rate	p_lower_rate_limit – p_max_sensor_rate
increase_rate	ppm/sec	Pace rate increase	0 – 14.5
decrease_rate	ppm/sec	Pace rate decrease	0 – 1.3
sensor_rate’	ppm	Sensor rate for modes	p_lower_rate_limit – p_max_sensor_rate
increase_rate’	ppm/sec	Increase rate for modes	0 – 14.5
decrease_rate’	ppm/sec	Decrease rate for modes	0 – 1.3
buffer	double	Last 25 values of accel	-4 – 4
pulse_detected	boolean	General pulse detection	{true, false}
refractory_period	ms	General refractory period	150–500 ± 8 ms
current_LRL	ppm	Current pacing rate	30 – 175 ppm

activity_pp	double	Peak to peak of activity signal	0 – 4
code	uint8	Last received code from DCM	0 – 5

4 Modules

4.1 Pacemaker Modes

4.1.1 AOO/VOO/AOOR/VOOR

4.1.1.1 Description

In AOO, VOO, AOOR and VOOR modes one chamber is paced at the indicated rate.

4.1.1.2 Variables

4.1.1.2.1 Measured

Name	Units/Type	Description	Range
t	ms	Time since last pulse	–

4.1.1.2.2 Parameters

No parameters

4.1.1.2.3 Controlled

No controlled variables

4.1.1.2.4 Internal

Name	Units/Type	Description	Range
XOO_pace_start	boolean	AOO or VOO indicates pace	{true, false}
sensor_rate’	ppm	Sensor rate for modes	p_lower_rate_limit – p_max_sensor_rate
increase_rate’	ppm/sec	Increase rate for modes	0 – 14.5
decrease_rate’	ppm/sec	Decrease rate for modes	0 – 1.3
current_LRL	ppm	Current pacing rate	30 – 175 ppm

4.1.1.3 Requirements

<table>
<tr><th>Source State</th><th>Event</th><th colspan="2">Condition</th><th>Condition Actions</th><th>Exit Actions</th><th>Destination State</th><th>Entry Actions</th></tr>
<tr><td>INITIAL</td><td>NONE</td><td colspan="2">NONE</td><td>NONE</td><td>NONE</td><td>PACE</td><td>current_LRL = sensor_rate</td></tr>
<tr><td rowspan="4">PACE</td><td rowspan="4">NONE</td><td rowspan="2">sensor_rate’ > current_LRL</td><td>current_LRL + increase_rate’ * t > sensor_rate’</td><td>current_LRL = sensor_rate</td><td rowspan="4">NONE</td><td rowspan="4">UPDATE_RATE</td><td rowspan="4">XOO_pace_start = true</td></tr>
<tr><td>current_LRL + increase_rate’ * t ≤ sensor_rate’</td><td>current_LRL += increase_rate’ * t</td></tr>
<tr><td rowspan="2">sensor_rate’ ≤ current_LRL</td><td>current_LRL – decrease_rate’ * t < sensor_rate’</td><td>current_LRL = sensor_rate</td></tr>
<tr><td>current_LRL – decrease_rate’ * t ≥ sensor_rate’</td><td>current_LRL -= decrease_rate’ * t</td></tr>
<tr><td>UPDATE_RATE</td><td>NONE</td><td colspan="2">after(60/current_LRL, sec)</td><td>NONE</td><td>t = elapsed(sec)</td><td>PACE</td><td>on after(1, msec):
XOO_pace_start = false</td></tr>
</table>

4.1.1.4 *Anticipated Changes*

AOO/VOO/AOOR/VOOR logic could be combined with AAI/VVI/AAIR/VVIR (4.1.2) logic by using parameter selection (4.1.4) to route false to pulse_detected (4.1.2.2.4) in the latter when in AOO/VOO/AOOR/VOOR modes.

4.1.2 AAI/VVI/AAIR/VVIR

4.1.2.1 *Description*

In AAI, VVI, AAIR and VVIR modes, one chamber is paced at the indicated rate but inhibited by sensed pulses in the same chamber.

4.1.2.2 *Variables*

4.1.2.2.1 Measured

Name	**Units/Type**	**Description**	**Range**
t	ms	Time since last pulse	–

4.1.2.2.2 Parameters

No parameters

4.1.2.2.3 Controlled

No controlled variables

4.1.2.2.4 Internal

Name	**Units/Type**	**Description**	**Range**
XXI_pace_start	boolean	AAI or VVI indicates pace	{true, false}
sensor_rate’	ppm	Sensor rate for modes	p_lower_rate_limit – p_max_sensor_rate
increase_rate’	ppm/sec	Increase rate for modes	0 – 14.5
decrease_rate’	ppm/sec	Decrease rate for modes	0 – 1.3
buffer	double	Last 25 values of accel	-4 – 4
pulse_detected	boolean	General pulse detection	{true, false}
refractory_period	ms	General refractory period	150–500 ± 8 ms
current_LRL	ppm	Current pacing rate	30 – 175 ppm

4.1.2.3 *Requirements*

<table>
<tr><th>Source State</th><th colspan="3">Condition</th><th>Condition Actions</th><th>Exit Actions</th><th>Destination State</th><th>Entry Actions</th></tr>
<tr><td>INITIAL</td><td colspan="3">NONE</td><td>NONE</td><td>NONE</td><td>WAIT</td><td>current_LRL = sensor_rate</td></tr>
<tr><td rowspan="2">WAIT</td><td colspan="3">pulse_detected == 1</td><td>NONE</td><td>t = elapsed(sec)</td><td>SENSE</td><td></td></tr>
<tr><td colspan="3">after(60/current_LRL – 0.001refractory_period + 0.001,sec)</td><td>NONE</td><td>t = elapsed(sec)</td><td>PACE</td><td></td></tr>
<tr><td rowspan="4">PACE</td><td rowspan="5">after(p_rp, msec)</td><td rowspan="2">sensor_rate’ > current_LRL</td><td>current_LRL + increase_rate’ * t > sensor_rate’</td><td>current_LRL = sensor_rate</td><td rowspan="5">t += elapsed(sec)</td><td rowspan="5">WAIT</td><td rowspan="4">XXI_pace_start = true
on after(1, msec)
XXI_pace_start = true</td></tr>
<tr><td>current_LRL + increase_rate’ * t ≤ sensor_rate’</td><td>current_LRL += increase_rate’ * t</td></tr>
<tr><td rowspan="3">sensor_rate’ ≤ current_LRL</td><td>current_LRL – decrease_rate’ * t < sensor_rate’</td><td>current_LRL = sensor_rate</td></tr>
<tr><td rowspan="2">current_LRL – decrease_rate’ * t ≥ sensor_rate’</td><td rowspan="2">current_LRL -= decrease_rate’ * t</td></tr>
<tr><td>SENSE</td><td>NONE</td></tr>
</table>

4.1.2.4 Anticipated Changes

See 4.1.1.4

4.1.3 DOO/DOOR

4.1.3.1 Description

In DOO and DOOR modes, both chambers are paced at the indicated rate, with fixed delay between atrial and ventricular pulses.

4.1.3.2 Variables

4.1.3.2.1 Measured

Name	Units/Type	Description	Range
t	ms	Time since last pulse	–

4.1.3.2.2 Parameters

Name	Units/Type	Description	Range
p_av_delay	ms	Delay between paced atrial and ventricular signals	70 – 300 ms ± 8 ms

4.1.3.2.3 Controlled

No controlled variables

4.1.3.2.4 Internal

Name	Units/Type	Description	Range
DOO_A_pace_start	boolean	DOO indicates atrial pace	{true, false}
DOO_V_pace_start	boolean	DOO indicates ventricular pace	{true, false}
DOO_AV_select	boolean	DOO indicates which chamber will be paced next	{true, false}
sensor_rate'	ppm	Sensor rate for modes	p_lower_rate_limit – p_max_sensor_rate
increase_rate'	ppm/sec	Increase rate for modes	0 – 14.5
decrease_rate'	ppm/sec	Decrease rate for modes	0 – 1.3
current_LRL	ppm	Current pacing rate	30 – 175 ppm

4.1.3.3 Requirements

<table>
<tr><th>Source State</th><th colspan="3">Condition</th><th>Condition Actions</th><th>Exit Actions</th><th>Destination State</th><th>Entry Actions</th></tr>
<tr><td>INITIAL</td><td colspan="3">NONE</td><td>NONE</td><td>NONE</td><td>PACE_VENT</td><td>current_LRL = sensor_rate</td></tr>
<tr><td rowspan="4">PACE_ATR</td><td rowspan="4">after(p_av_delay,msec)</td><td rowspan="2">sensor_rate’ > current_LRL</td><td>current_LRL + increase_rate’ * t > sensor_rate’</td><td>current_LRL = sensor_rate</td><td rowspan="4">t += elapsed(sec)</td><td rowspan="4">PACE_VENT</td><td rowspan="4">DOO_A_pace_start = true on after(1, msec)
DOO_A_pace_start = true
DOO_AV_select = V</td></tr>
<tr><td>current_LRL + increase_rate’ * t ≤ sensor_rate’</td><td>current_LRL += increase_rate’ * t</td></tr>
<tr><td rowspan="2">sensor_rate’ ≤ current_LRL</td><td>current_LRL – decrease_rate’ * t < sensor_rate’</td><td>current_LRL = sensor_rate</td></tr>
<tr><td>current_LRL – decrease_rate’ * t ≥ sensor_rate’</td><td>current_LRL -= decrease_rate’ * t</td></tr>
<tr><td>PACE_VENT</td><td colspan="3">after(60/current_LRL – p_av_delay/1000, sec)</td><td>NONE</td><td>t = elapsed(sec)</td><td>PACE_ATR</td><td>DOO_V_pace_start = true on after(1, msec)
DOO_V_pace_start = true
DOO_AV_select = A</td></tr>
</table>

4.1.3.4 Anticipated Changes

DOO/DOOR would be the basis for extending to the DXXX modes by adding sensed signal states as appropriate.

4.1.4 PARAMETER SELECTION

4.1.4.1 Description

Parameter selection parses parameter information to feed to the actual mode logic, then routes the mode logic output to the correct signal outputs.

4.1.4.2 Variables

4.1.4.2.1 Measured

No measured variables

4.1.4.2.2 Parameters

Name	Units/Type	Description	Range
p_mode	–	Pacemaker operational mode	{AOO,VOO,AAI,VVI, DOO, AOOR, VOOR, AAIR, VVIR, DOOR}
p_lower_rate_limit	ppm	Lowest allowable heart rate	30 – 175 ± 8 ms
p_av_delay	ms	Delay between paced atrial and ventricular signals	70 – 300 ms ± 8 ms
p_vrp	ms	Ventricular Refractory Period	150–500 ± 8 ms
p_arp	ms	Atrial Refractory Period	150–500 ± 8 ms

4.1.4.2.3 Controlled

No controlled variables

4.1.4.2.4 Internal

Name	Units/Type	Description	Range
h_atr_pulse_detected	boolean	Pulse detected in atrium	{true, false}
h_vent_pulse_detected	boolean	Pulse detected in ventricle	{true, false}
XOO_pace_start	boolean	AOO or VOO indicates pace	{true, false}

XXI_pace_start	boolean	AAI or VVI indicates pace	{true, false}
DOO_A_pace_start	boolean	DOO indicates atrial pace	{true, false}
DOO_V_pace_start	boolean	DOO indicates ventricular pace	{true, false}
DOO_AV_select	boolean	DOO indicates which chamber will be paced next	{true, false}
A_pace_start	boolean	Signal to pace atrium	{true, false}
V_pace_start	boolean	Signal to pace ventricle	{true, false}
AV_select	boolean	Selects which chamber will be paced next	{A, V}
sensor_rate	ppm	Rate adaptivity indicated rate	p_lower_rate_limit – p_max_sensor_rate
increase_rate	ppm/sec	Pace rate increase	0 – 14.5
decrease_rate	ppm/sec	Pace rate decrease	0 – 1.3
sensor_rate’	ppm	Sensor rate for modes	p_lower_rate_limit – p_max_sensor_rate
increase_rate’	ppm/sec	Increase rate for modes	0 – 14.5
decrease_rate’	ppm/sec	Decrease rate for modes	0 – 1.3
pulse_detected	boolean	General pulse detection	{true, false}
refractory_period	ms	General refractory period	150–500 ± 8 ms

4.1.4.3 Requirements

mode	sensor_rate’	increase_rate’	decrease_rate’	pulse_detected	refractory_period	A_pace_start	V_pace_start	AV_select
AOO	p_lower_rate_limit	0	0	X	X	XOO_pace_start	0	A
VOO				X	X	0	XOO_pace_start	V
AAI				h_atr_pulse_detected	p_arp	XXI_pace_start	0	A
VVI				h_vent_pulse_detected	p_vrp	0	XXI_pace_start	V
DOO				X	X	DOO_A_pace_start	DOO_V_pace_start	DOO_AV_select
AOOR	sensor_rate	increase_rate	decrease_rate	X	X	XOO_pace_start	0	A
VOOR				X	X	0	XOO_pace_start	V
AAIR				h_atr_pulse_detected	p_arp	XXI_pace_start	0	A
VVIR				h_vent_pulse_detected	p_vrp	0	XXI_pace_start	V
DOOR				X	X	DOO_A_pace_start	DOO_V_pace_start	DOO_AV_select

4.1.4.4 Anticipated Changes

If more modes were to be implemented, parameter would have to take them into account in order to route the input and output signals correctly.

4.2 Rate Adaptivity

4.2.1 Description

The rate adaptivity module indicates the rate at which pacing should occur according to the activity as sensed through the on-board accelerometer. It also calculates the rate at which the pacing rate changes as defined by the rate adaptivity parameters.

4.2.2 Variables

4.2.2.1 Measured

Name	Units/Type	Description	Range
accel	double x 3	Proper acceleration in g of pacemaker in local (x,y,z)	-4 – 4

4.2.2.2 Parameters

Name	Units/Type	Description	Range
p_lower_rate_limit	ppm	Lowest allowable heart rate	30 – 175 ± 8 ms
p_max_sensor_rate	ppm	Maximum sensor rate indicated by rate adaptivity	50 – 175 ± 4 ppm
p_activity_threshold	–	Minimum activity level for rate adaptivity	{V-Low, Low, Med-Low, Med, Med-High, High, V-high}
p_reaction_time	sec	Time required for pacing rate to rise from lower rate limit to max sensor rate	10 – 50 ± 3 sec
p_response_factor	–	Indicates response to activity levels above threshold	{true, false}
p_recovery_time	min	Maximum allowable pacing rate decrease	2 – 16 ± 30 sec

4.2.2.3 Controlled

No controlled variables

4.2.2.4 Internal

Name	Units/Type	Description	Range
sensor_rate	ppm	Rate adaptivity indicated rate	p_lower_rate_limit – p_max_sensor_rate
increase_rate	ppm/sec	Pace rate increase	0 – 14.5
decrease_rate	ppm/sec	Pace rate decrease	0 – 1.3
buffer	double	Last 25 values of accel	-4 – 4
activity_pp	double	peak to peak of activity signal	0 – 4

4.2.3 Requirements

Variable	Value
activity_pp	max(buffer) – min(buffer)
increase_rate	(p_max_sensor_rate – p_lower_rate_limit) / p_reaction_time
decrease_rate	(p_max_sensor_rate – p_lower_rate_limit) / (60 * p_recovery_time)
activity_overdrive	4 * p_response_factor * (p_activity_pp – p_activity_threshold)
sensor_rate	min(p_max_sensor_rate, max(p_lower_rate_limit, activity_overdrive))

4.2.4 Anticipated Changes
Should a different design for rate adaptivity be selected, this module would need reworking to match those requirements.

4.3 Hardware Interface

4.3.1 PACING

4.3.1.1 Description

The pacing module monitors the pace start and AV select lines and controls which level to charge the pacing capacitor at and which chamber to pace.

4.3.1.2 Variables

4.3.1.2.1 Measured
No measured variables

4.3.1.2.2 Parameters

Name	Units/Type	Description	Range
p_atr_amplitude	V	Amplitude of pulse delivered to atrium	0 – 5 ± 12%
p_vent_amplitude	V	Amplitude of pulse delivered to ventricle	0 – 5 ± 12%
p_atr_pulse_width	ms	Pulse width of atrial pace	1 – 30 ± 0.2 ms
p_vent_pulse_width	ms	Pulse width of ventricular pace	1 – 30 ± 0.2 ms

4.3.1.2.3 Controlled

Name	Units/Type	Description	Range
PACE_CHARGE_CTRL	boolean	PWM connected to primary capacitor	{true, false}
ATR_PACE_CTRL	boolean	Atrial ring connected to primary capacitor	{true, false}
VENT_PACE_CTRL	boolean	Ventricular ring connected to primary capacitor	{true, false}
ATR_GND_CTRL	boolean	Atrial ring connected to ground	{true, false}
VENT_GND_CTRL	boolean	Ventricular ring connected to ground	{true, false}
PACE_GND_CTRL	boolean	Atrial and Ventricular tip connected to blocking capacitor	{true, false}
Z_ATR_CTRL	boolean	Impedance circuit connected to atrial ring	{true, false}
Z_VENT_CTRL	boolean	Impedance circuit connected to ventricular ring	{true, false}
PACING_REF_PWM	%	Reference PWM for primary capacitor	0–100

4.3.1.2.4 Internal

Name	Units/Type	Description	Range
A_pace_start	boolean	Signal to pace atrium	{true, false}
V_pace_start	boolean	Signal to pace ventricle	{true, false}
AV_select	boolean	Selects which chamber will be paced next	{A, V}

4.3.1.3 Requirements

Source State	Event	Condition	Condition Actions	Exit Actions	Destination State	Entry Actions
INITIAL	NONE	NONE	NONE	NONE	C22_Charge	VENT_GND_CTRL=false Z_VENT_CTRL=false Z_ATR_CTRL=false ATR_GND_CTRL=false
C22_Charge	NONE	V_pace_start == false AND A_pace_start == false	NONE	NONE	Buffer	VENT_PACE_CTRL=false ATR_PACE_CTRL=false PACE_CHARGE_CTRL=true PACE_GND_CTRL=true
Buffer	NONE	A_pace_start == true	NONE	NONE	A_pacing	NONE
		V_pace_start == true	NONE	NONE	V_pacing	NONE
A_pacing	NONE	after(p_atr_pulse_width)	NONE	NONE	C21_Discharge_A	PACE_CHARGE_CTRL=false VENT_PACE_CTRL=false VENT_GND_CTRL=false ATR_GND_CTRL=false ATR_PACE_CTRL=true
C21_Discharge_A	NONE	NONE	NONE	NONE	C22_Charge	ATR_PACE_CTRL=false ATR_GND_CTRL=true
V_pacing	NONE	after(p_vent_pulse_width)	NONE	NONE	C21_Discharge	PACE_CHARGE_CTRL=false ATR_PACE_CTRL=false ATR_GND_CTRL=false VENT_GND_CTRL=false VENT_PACE_CTRL=true
C21_Discharge_V	NONE	NONE	NONE	NONE	C22_Charge	VENT_PACE_CTRL=false; VENT_GND_CTRL=true;

4.3.1.4 Anticipated Changes

A change in hardware would necessitate reconfiguring the output signals to match the new hardware.

4.3.2 SENSING

4.3.3 Description

The sensing module sets the levels of the reference capacitors and parses the signal to output pulses when natural heart pulses are detected.

4.3.4 Variables

4.3.4.1.1 Measured

Name	Units/Type	Description	Range
ATR_CMP_DETECT	boolean	Atrial signal voltage higher than threshold	{true, false}
VENT_CMP_DETECT	boolean	Ventricular signal voltage higher than threshold	{true, false}

4.3.4.1.2 Parameters

Name	Units/Type	Description	Range
p_atr_sensitivity	V	Minimum voltage over which signal in atrium is classified as a pulse	0 – 5 ± 2%
p_vent_sensitivity	V	Minimum voltage over which signal in ventricle is classified as a pulse	0 – 5 ± 2%

4.3.4.1.3 Controlled

Name	Units/Type	Description	Range
ATR_CMP_REF_PWM	%	Reference PWM for atrial signal comparator	0–100
VENT_CMP_REF_PWM	%	Reference PWM for ventricular signal comparator	0–100
FRONTEND_CTRL	boolean	Sensing circuit connected to leads	{true, false}

4.3.4.1.4 Internal

Name	Units/Type	Description	Range
h_atr_pulse_detected	boolean	Pulse detected in atrium	{true, false}
h_vent_pulse_detected	boolean	Pulse detected in ventricle	{true, false}

4.3.4.2 Requirements

Variable	Value
h_atr_pulse_detected	ATR_CMP_DETECT
h_vent_pulse_detected	VENT_CMP_DETECT
ATR_CMP_REF_PWM	p_atr_sensitivity / (5 V) * 100 %
VENT_CMP_REF_PWM	p_vent_sensitivity / (5 V) * 100 %
FRONTEND_CTRL	1

4.3.4.3 Anticipated Changes

A change in hardware would necessitate reconfiguring the input signals to match the new hardware.

4.4 DCM Communication

4.4.1 In

4.4.1.1 Description

The communication-in module monitors the UART Rx signal for messages from the DCM and updates the relevant variables on the pacemaker.

4.4.1.2 Variables

4.4.1.2.1 Measured

Name	Units/Type	Description	Range
Rx	uint8 x 17	UART in buffer	0 – 255
Status	uint8	Indicates whether UART buffer is full	{0, 32}

4.4.1.2.2 Parameters

Name	Units/Type	Description	Range
p_mode	–	Pacemaker operational mode	{AOO,VOO,AAI,VVI, DOO, AOOR, VOOR, AAIR, VVIR, DOOR}
p_lower_rate_limit	ppm	Lowest allowable heart rate	30 – 175 ± 8 ms
p_av_delay	ms	Delay between paced atrial and ventricular signals	70 – 300 ms ± 8 ms
p_atr_amplitude	V	Amplitude of pulse delivered to atrium	0 – 5 ± 12%
p_vent_amplitude	V	Amplitude of pulse delivered to ventricle	0 – 5 ± 12%
p_atr_sensitivity	V	Minimum voltage over which signal in atrium is classified as a pulse	0 – 5 ± 2%
p_vent_sensitivity	V	Minimum voltage over which signal in ventricle is classified as a pulse	0 – 5 ± 2%
p_atr_pulse_width	ms	Pulse width of atrial pace	1 – 30 ± 0.2 ms
p_vent_pulse_width	ms	Pulse width of ventricular pace	1 – 30 ± 0.2 ms
p_vrp	ms	Ventricular Refractory Period	150–500 ± 8 ms
p_arp	ms	Atrial Refractory Period	150–500 ± 8 ms
p_max_sensor_rate	ppm	Maximum sensor rate indicated by rate adaptivity	50 – 175 ± 4 ppm
p_activity_threshold	–	Minimum activity level for rate adaptivity	{V-Low, Low, Med-Low, Med, Med-High, High, V-high}
p_reaction_time	sec	Time required for pacing rate to rise from lower rate limit to max sensor rate	10 – 50 ± 3 sec
p_response_factor	–	Indicates response to activity levels above threshold	{true, false}
p_recovery_time	min	Maximum allowable pacing rate decrease	2 – 16 ± 30 sec

4.4.1.2.3 Controlled

No controlled variables

4.4.1.2.4 Internal

Name	Units/Type	Description	Range
code	uint8	Last received code from DCM	0 – 5

4.4.1.3 Requirements

Status	Rx(1)	parameters	code
0	1	Rx(2:17)	Rx(1)
	X	no change	
32	X	no change	X

4.4.1.4 Anticipated Changes

A change in hardware would necessitate reconfiguring the input signals to match the new hardware.

4.4.2 Out

4.4.2.1 Description

The communications-out module controls the UART Tx signal to send the pacemaker's serial number, echo parameter data, or send atrial/ventricular signal data to the DCM.

4.4.2.2 Variables

4.4.2.2.1 Measured

Name	Units/Type	Description	Range
ATR_SIGNAL	double	electrocardiogram measurement of atrial signal	0 – 1
VENT_SIGNAL	double	electrocardiogram measurement of ventricular signal	0 – 1

4.4.2.2.2 Parameters

Name	Units/Type	Description	Range
p_mode	–	Pacemaker operational mode	{AOO,VOO,AAI,VVI, DOO, AOOR, VOOR, AAIR, VVIR, DOOR}
p_lower_rate_limit	ppm	Lowest allowable heart rate	30 – 175 ± 8 ms
p_av_delay	ms	Delay between paced atrial and ventricular signals	70 – 300 ms ± 8 ms
p_atr_amplitude	V	Amplitude of pulse delivered to atrium	0 – 5 ± 12%
p_vent_amplitude	V	Amplitude of pulse delivered to ventricle	0 – 5 ± 12%

p_atr_sensitivity	V	Minimum voltage over which signal in atrium is classified as a pulse	0 – 5 ± 2%
p_vent_sensitivity	V	Minimum voltage over which signal in ventricle is classified as a pulse	0 – 5 ± 2%
p_atr_pulse_width	ms	Pulse width of atrial pace	1 – 30 ± 0.2 ms
p_vent_pulse_width	ms	Pulse width of ventricular pace	1 – 30 ± 0.2 ms
p_vrp	ms	Ventricular Refractory Period	150–500 ± 8 ms
p_arp	ms	Atrial Refractory Period	150–500 ± 8 ms
p_max_sensor_rate	ppm	Maximum sensor rate indicated by rate adaptivity	50 – 175 ± 4 ppm
p_activity_threshold	–	Minimum activity level for rate adaptivity	{V-Low, Low, Med-Low, Med, Med-High, High, V-high}
p_reaction_time	sec	Time required for pacing rate to rise from lower rate limit to max sensor rate	10 – 50 ± 3 sec
p_response_factor	–	Indicates response to activity levels above threshold	{true, false}
p_recovery_time	min	Maximum allowable pacing rate decrease	2 – 16 ± 30 sec

4.4.2.2.3 Controlled

Name	Units/Type	Description	Range
Tx	uint8 x 16	UART out buffer	0 – 255

4.4.2.2.4 Internal

Name	Units/Type	Description	Range
code	uint8	Last received code from DCM	0 – 5

4.4.2.3 Requirements

code	Tx
0	serial number
1	X
2	parameters
3	[ATR_SIGNAL, 0]
4	[VENT_SIGNAL, 0]
5	[ATR_SIGNAL, VENT_SIGNAL]

4.4.2.4 Anticipated Changes

A change in hardware would necessitate reconfiguring the output signals to match the new hardware.

5 Design Decisions

5.1 Pacemaker Modes

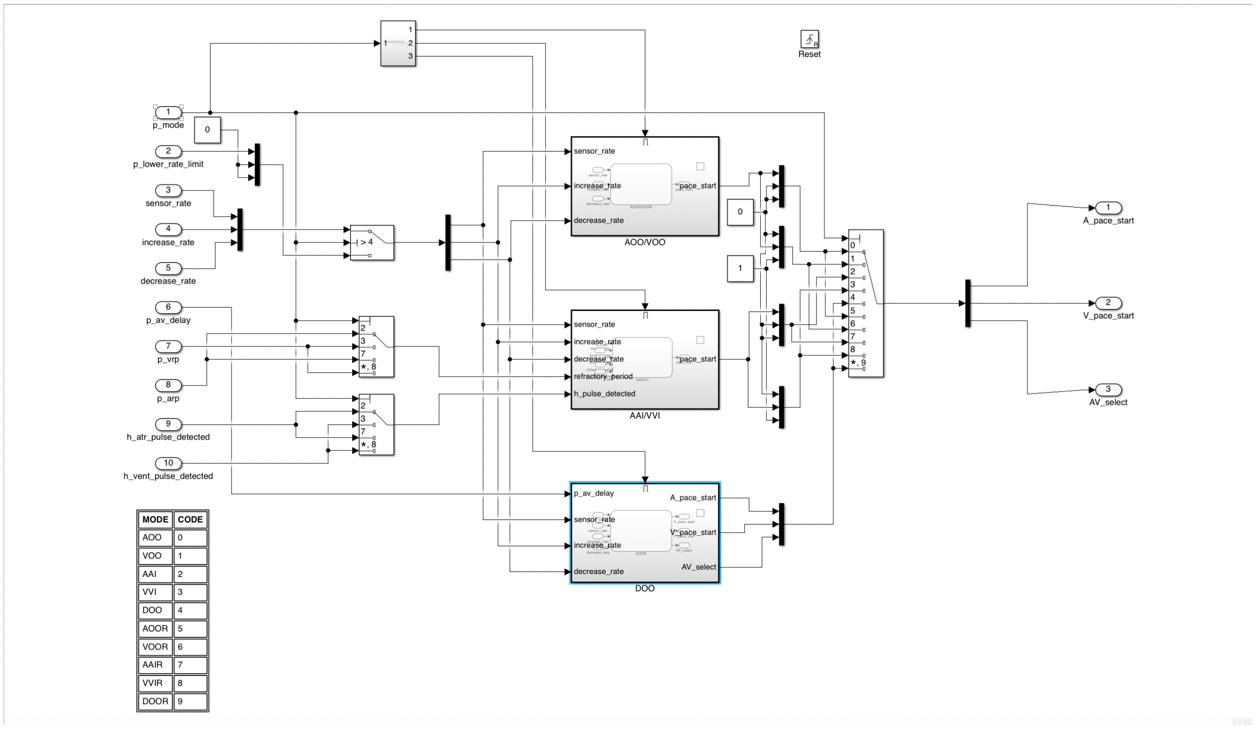


Figure 1: Mode Subsystem

The main logic of the pacemaker is in three Stateflow charts interacting mainly with abstracted variables so as to effectively achieve hardware hiding. There is one Stateflow chart for AOO, VOO, AOOR and VOOR modes, one Stateflow chart for AAI, VVI, AAIR and VVIR modes, and one Stateflow chart for DOO and DOOR modes, of which only one is enabled at one time. The grouped modes are all practically identical in implementation, the only differences being input and output signal routing (which is handled by 4.1.4 Parameter Selection). The sharing of Stateflow charts allows for greater maintainability due to the reduction in code.

In all modes, if the sensor indicated rate is different than the current pacing rate, upon pacing, the current pacing rate is increased or decreased at the appropriate rate given the time spent in the last waiting interval. The rate change is assumed to be linear with time. Since maximum sensor rate is defined to be independently programmable from the upper rate limit, no use was found for the upper rate limit in these modes and was excluded in this design.

That pacing should commence is indicated by a 1 ms pulse on the appropriate out signal. The AV select signal tells the hardware interface which level the next pacing is anticipated to be.

Additionally, to ensure correct behaviour, the mode module is reset upon receiving new parameters.

5.1.1 AOO/VOO/AOOR/VOOR

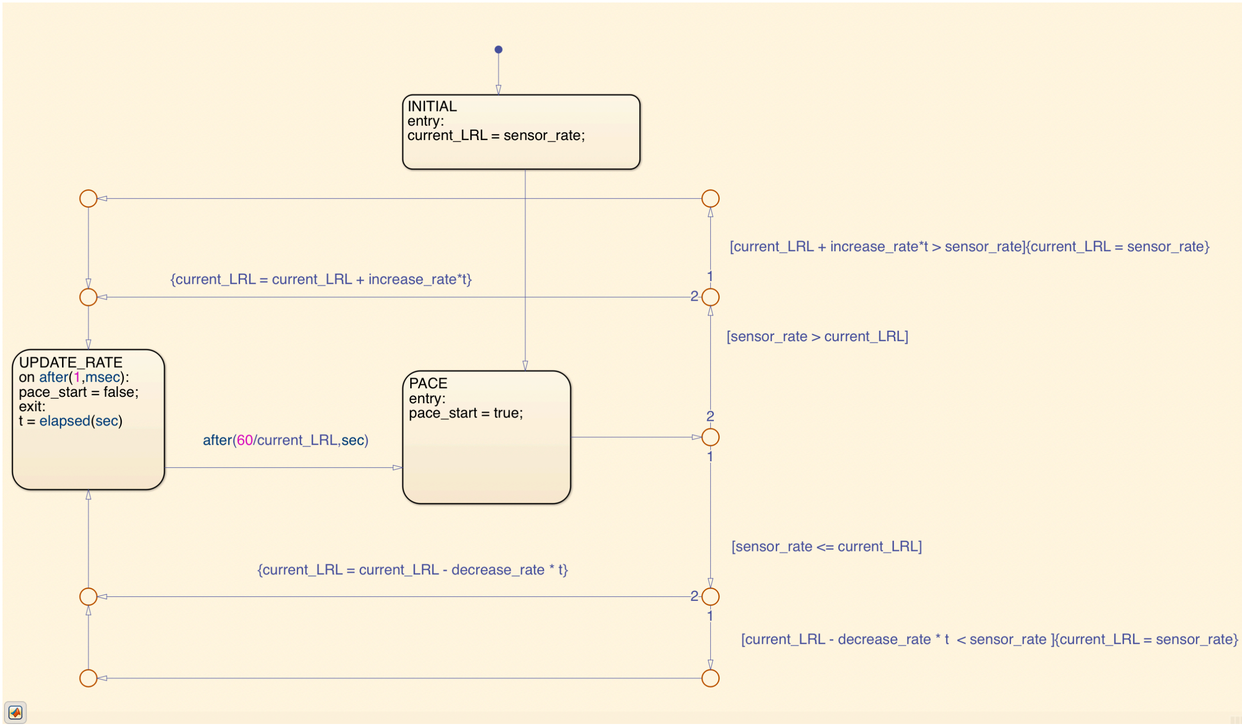


Figure 2: AOO/VOO/AOOR/VOOR Stateflow chart

The AOO, VOO, AOOR and VOOR modes do not require sensing of the heart, and so simply cycle between pacing and waiting states.

5.1.2 AAI/VVI/AAIR/VVIR

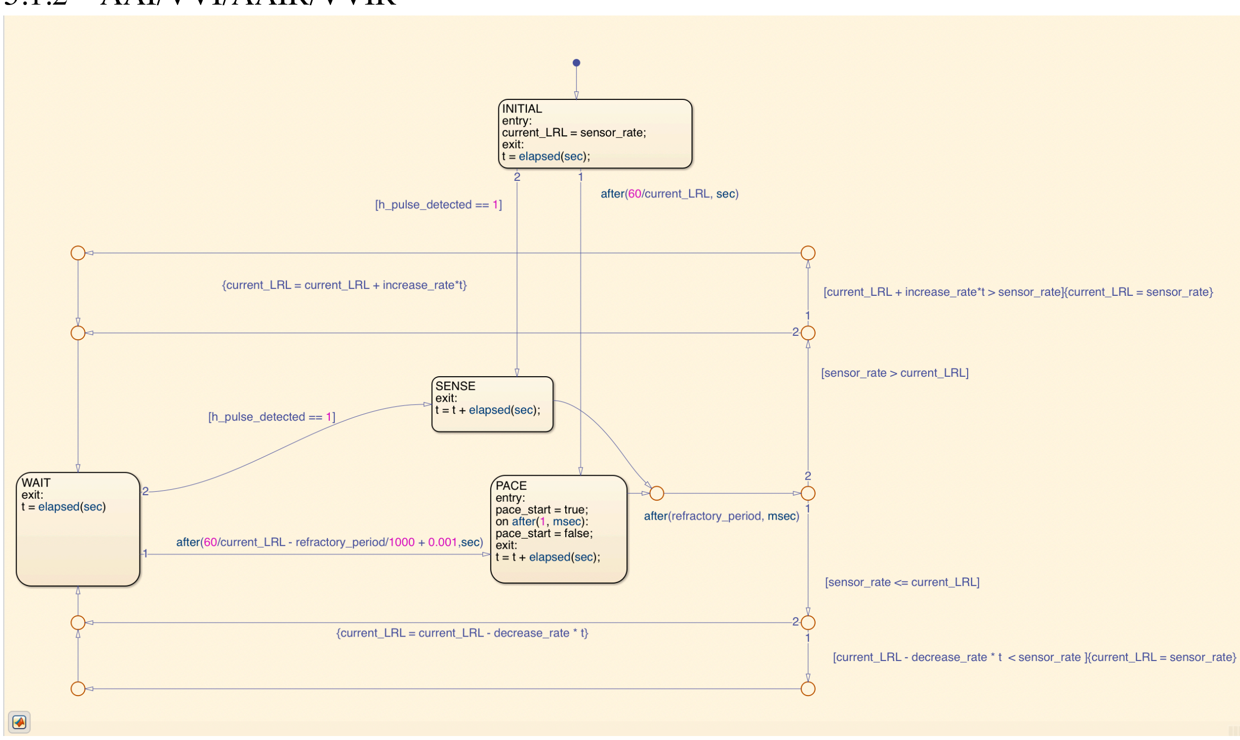


Figure 3: AAI/VVI/AAIR/VVIR Stateflow chart

The AAI, VVI, AAIR and VVIR modes have a similar structure as the XOO modes. Additionally, the pacing state can be bypassed by the sensing of a spontaneous pulse, if said pulse occurs after the refractory period (in which spontaneous pulses have no effect). An additional millisecond is added to the wait interval to ensure that if the heart is spontaneously beating at exactly the current pacing rate, the pacemaker does not pace unnecessarily.

5.1.3 DOO/DOOR

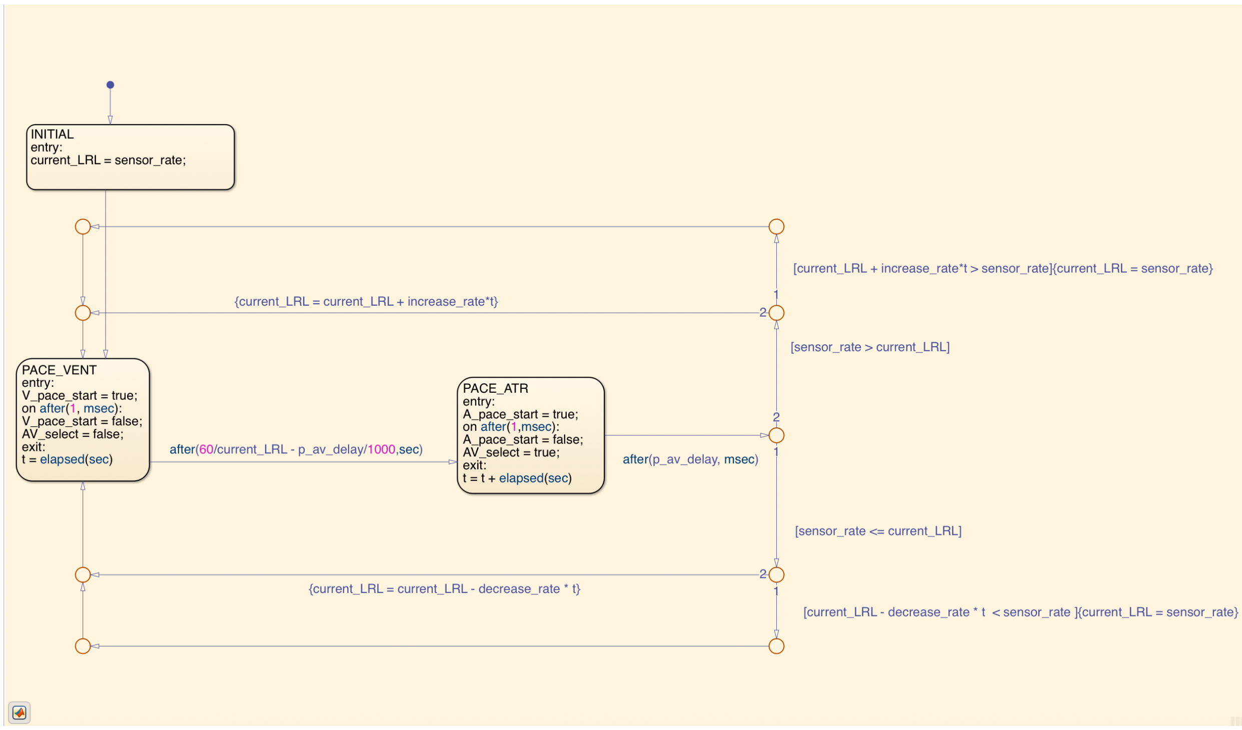


Figure 4: DOO/DOOR Stateflow chart

The DOO and DOOR states are very similar to the XOO states, except that here instead of cycling between pacing and waiting states, atrial and pacing states are cycled. After every atrial pace, AV_select switches to prepare the capacitor charge for a ventricular pace, and vice versa. Additionally, the fixed atrial-ventricular delay is implemented after every atrial pulse.

5.2 Rate Adaptivity

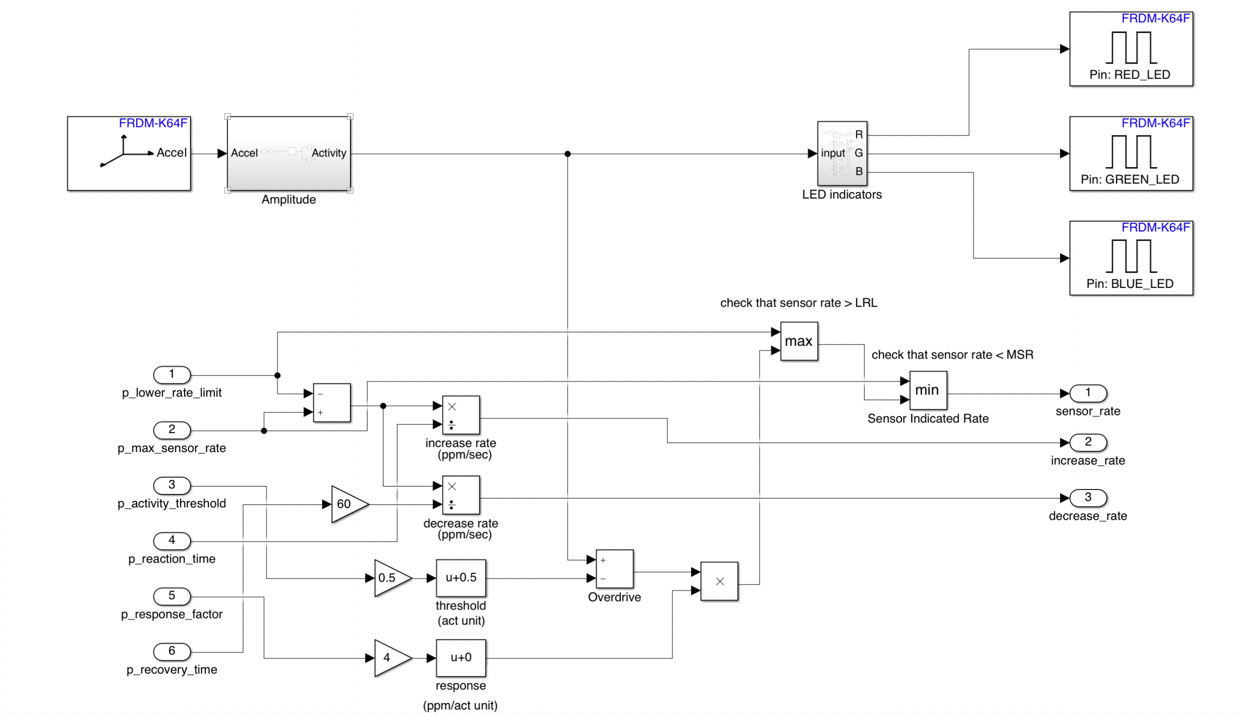


Figure 5: Rate Adaptivity Subsystem

In order to implement rate adaptivity, the activity level is interpreted as the peak-to-peak amplitude of the total accelerometer signal, i.e. $\sqrt{a_x^2 + a_y^2 + a_z^2}$, where a_x, a_y and a_z are the proper accelerations in the local x, y, and z axes respectively. The amplitude is found by sampling the signal from the accelerometer 25 times per second and subtracting the minimum from the maximum of the buffer.

The sensor-indicated rate is assumed to be linearly related to how much the activity level exceeds the activity threshold. By experiment, the activity level can comfortably vary between 0 and 4 units. Thus, the seven activity thresholds were evenly distributed in that range, with V-Low mapped to 0.5 and V-High mapped to 3.5. The response factor multiplied by 4 is then the slope of the response level (in ppm/activity unit) when activity exceeds the threshold. The sensor indicated rate is then checked against the lower rate limit and the maximum sensor rate, and if it falls short of the former or exceeds the latter, it is set to the appropriate value.

The rate of pacing rate increase and decrease is assumed to be linear with time. See 4.2.3 for detailed equations.

5.3 Hardware Interface

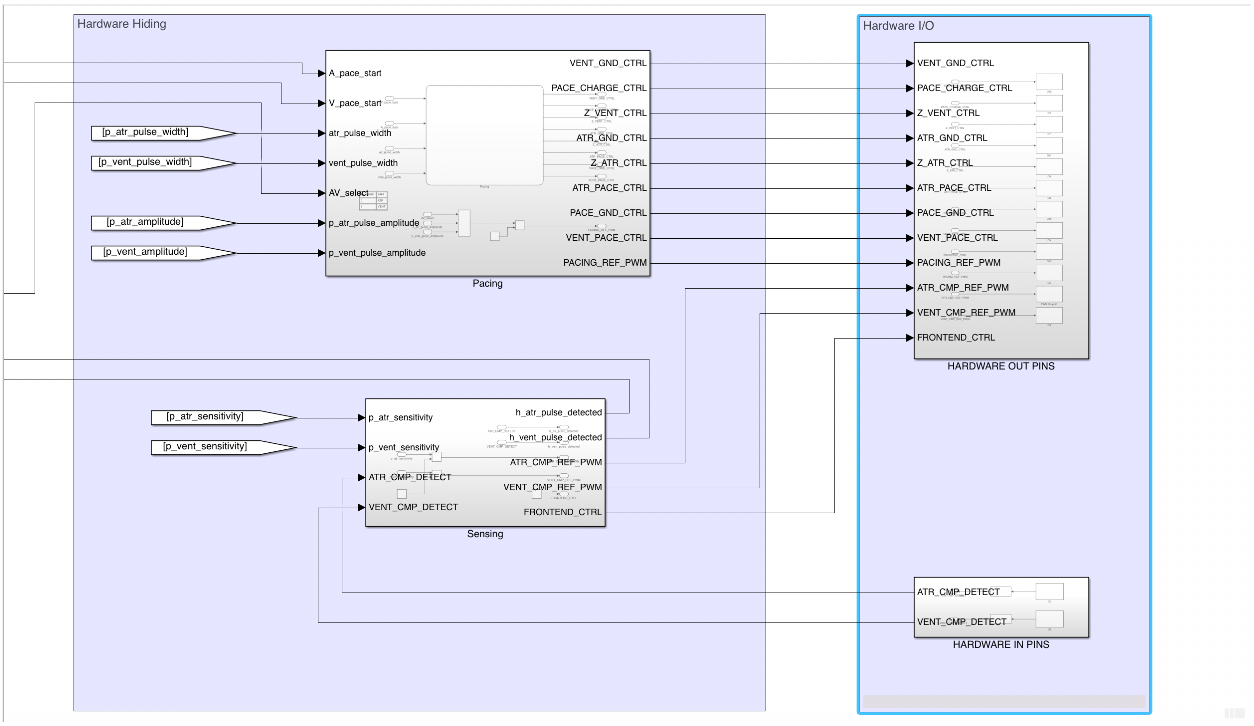


Figure 6: Hardware Interface subsystems

The purpose of the hardware interface is to abstract the IN and OUT variables of the pacemaker so that the main logic of the pacemaker could be easily transferred to any hardware system. This ensures that the only necessary changes would be to the logic detailing how the determined instructions should be best executed on the hardware. The hardware interface need only accept 1 ms pulsed pace atrium/ventricle signals and an atrial-ventricular level selector signal, while outputting 1 ms pulses when atrial/ventricular signals exceed their respective sensitivities.

5.3.1 Pacing

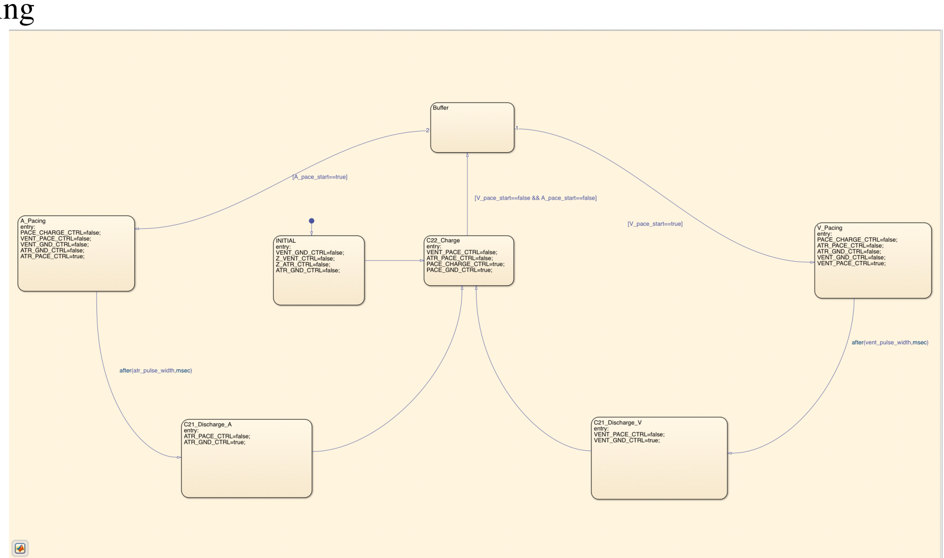


Figure 7: Pacing Stateflow chart

The pacing module waits in a buffer state until a pulse is detected on either the A_pace_start or V_pace_start lines, upon which it sets the appropriate flags to pace the heart. After a delay corresponding to the pulse width, flags are set to begin charging the pacing capacitor again while discharging the blocking capacitor. The buffer state is implemented as a safeguard against looping due to a non-deasserted pacing signal pulse.

5.3.2 Sensing

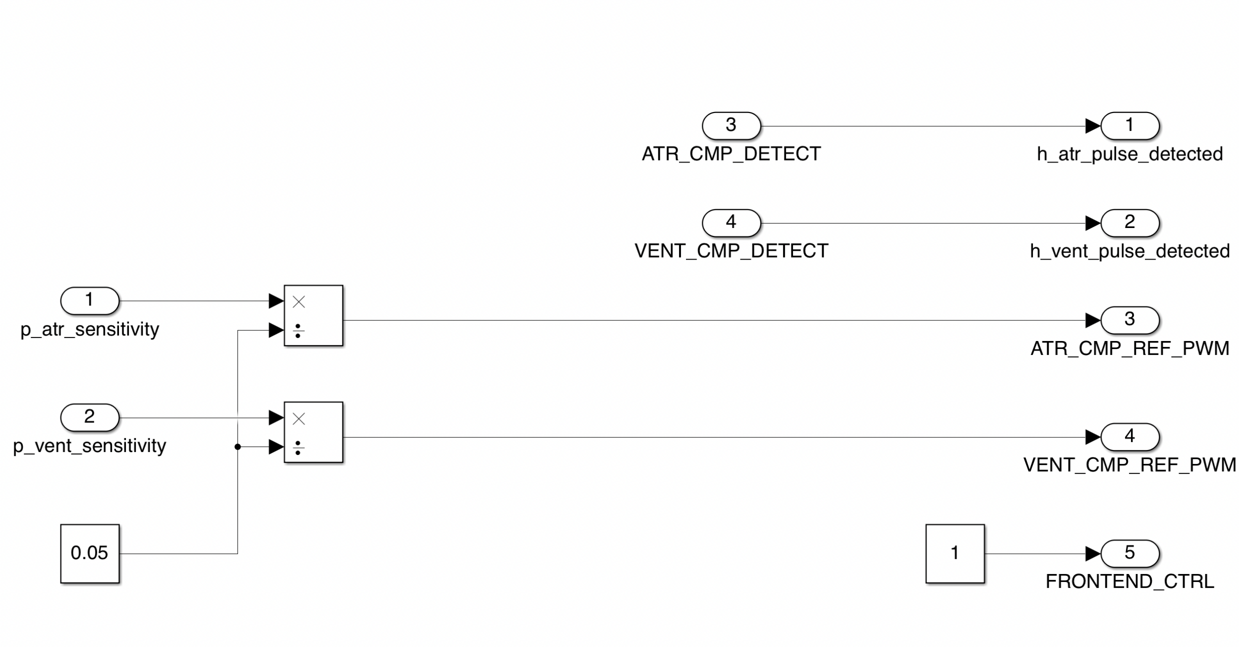


Figure 8: Sensing Subsystem

The sensing module simply sets the appropriate PWMs for the atrial and ventricular reference capacitors, while turning on the FRONTEND_CTRL and routing the natural pulse detection flags to the h_atr_pulse_detected and h_vent_pulse_detected variables.

5.4 DCM Communication

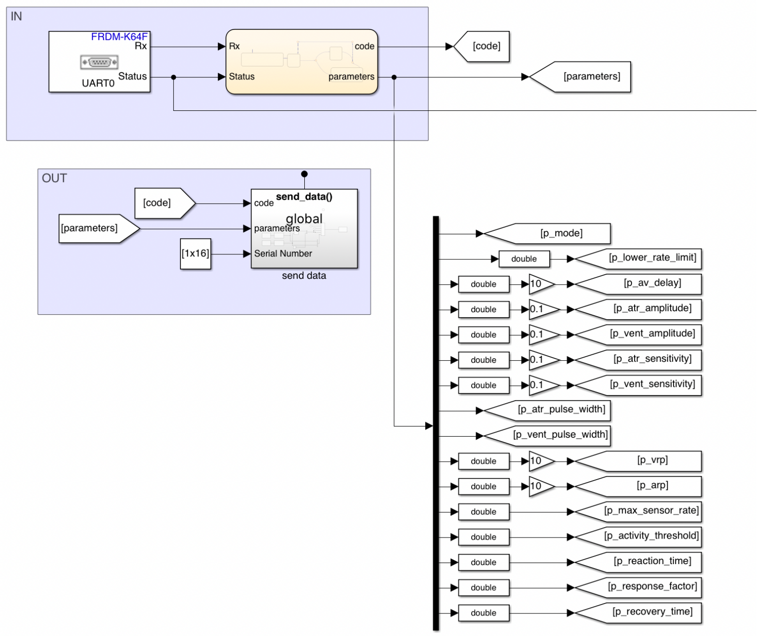


Figure 9: Communications Subsytems

The DCM Communication module handles all external communication. In a similar manner to the hardware interface, it presents abstracted variables to the system while interacting itself with the specific IN and OUT variables. UART communication was chosen for this design.

5.4.1 In

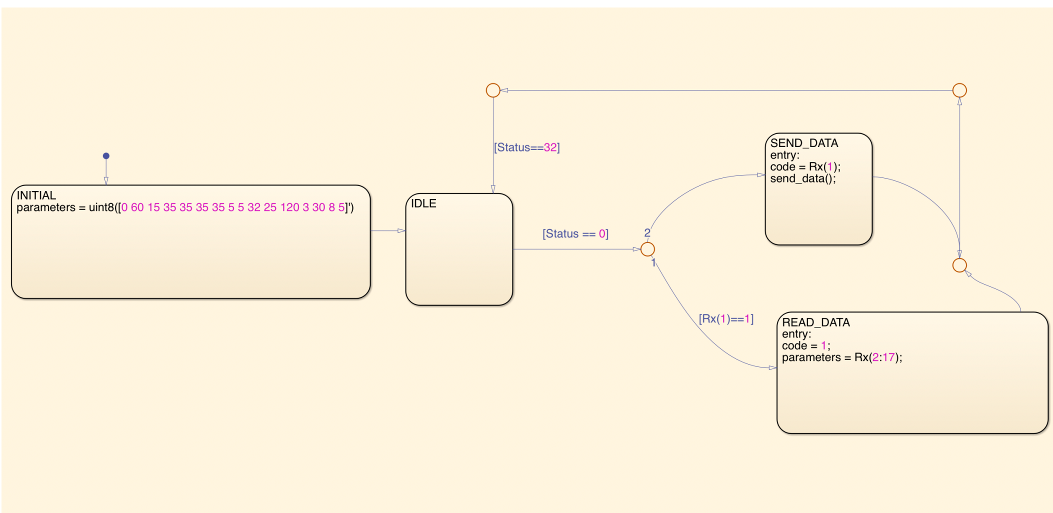


Figure 10: Communications In Stateflow chart

The In module reads the Rx buffer when Status indicates it is full and updates the parameter data or sends data to the DCM depending on the code received.

5.4.2 Out

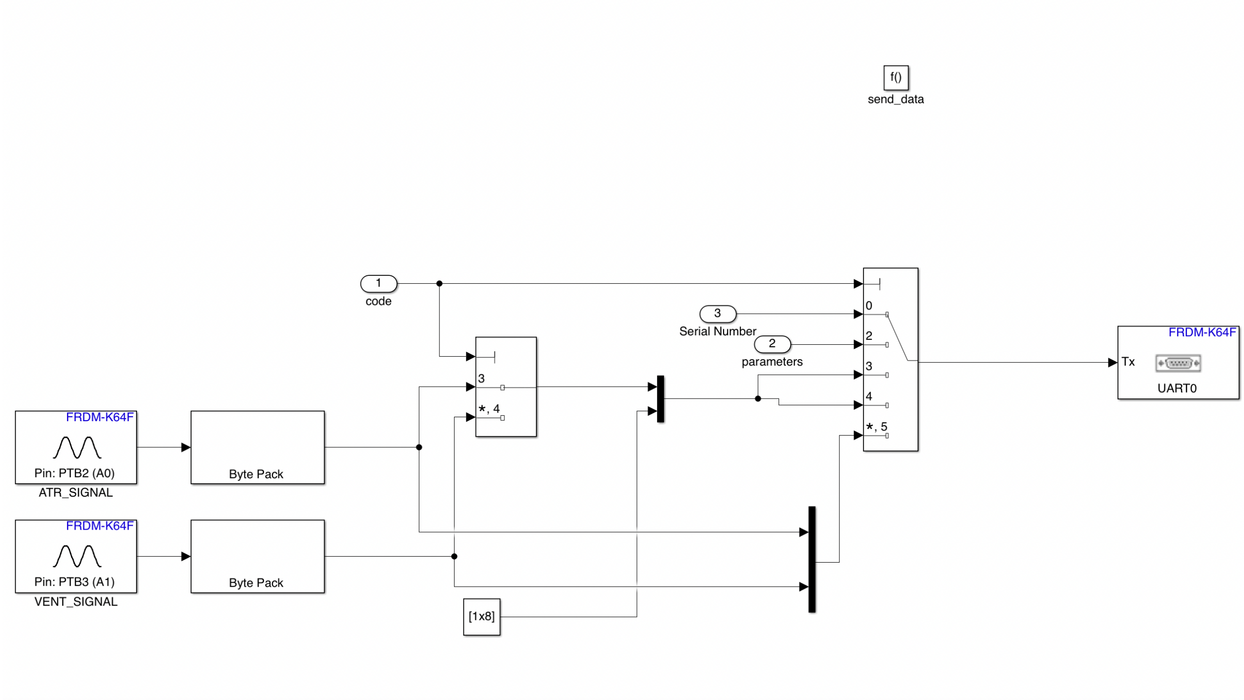


Figure 11: Communications Out Stateflow chart

The out module is only activated when a code of 0, 2, 3, 4 or 5 is received. Data is sent out via UART as detailed in 4.4.2.3.

6 Testing

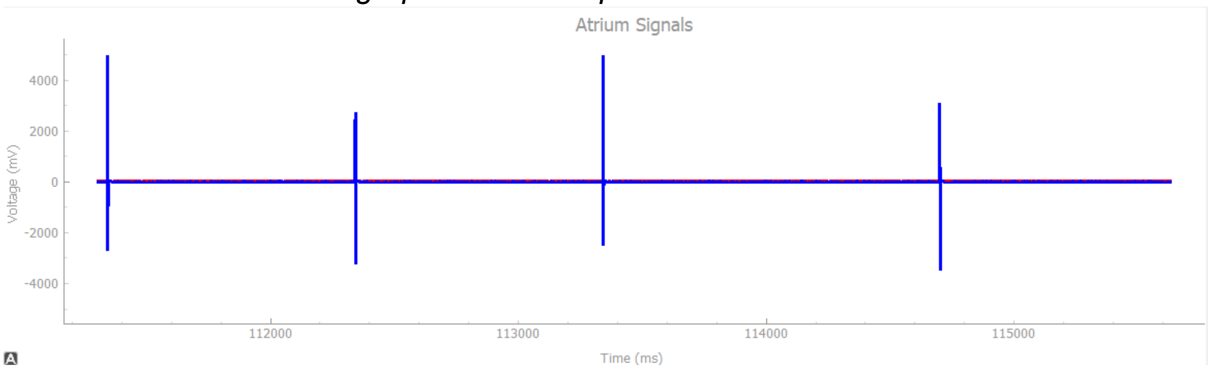
6.1 AOO

Chamber paced: Atrium
Chamber sensed: None
Response to Sensing: None

Test Cases:

a) <u>Natural Atrium: **OFF** | Natural Ventricle: **OFF**</u>
In AOO mode, as we are not sensing any chamber, only a single test case (when both atrium and ventricle are not working) can demonstrate correctness of our pacemaker.

the graph of artificial pulse from HeartView



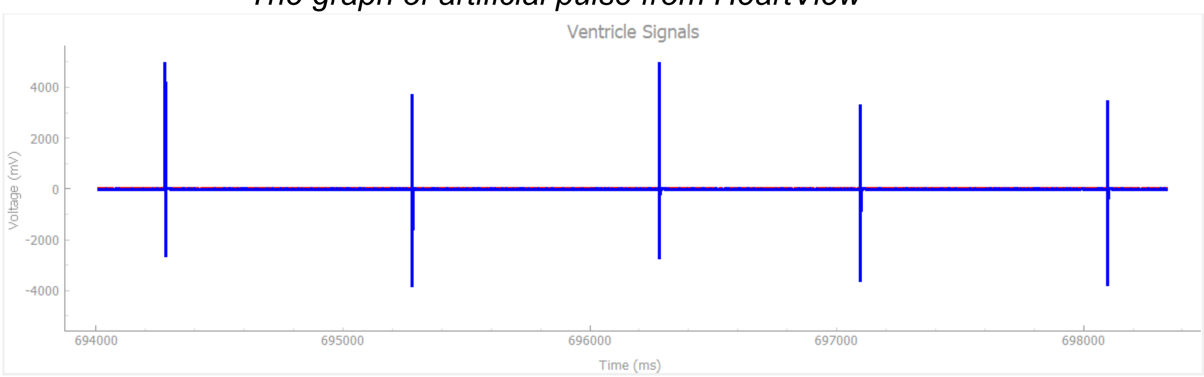
6.2 VOO

Chamber paced: Ventricle
Chamber sensed: None
Response to Sensing: None

Test Cases:

a) <u>Natural Atrium: **OFF** | Natural Ventricle: **OFF**</u>
In VOO mode also, as we are not sensing any chamber, only a single test case (when both atrium and ventricle are not working) can demonstrate correctness of our pacemaker.

The graph of artificial pulse from HeartView



6.3 AAI

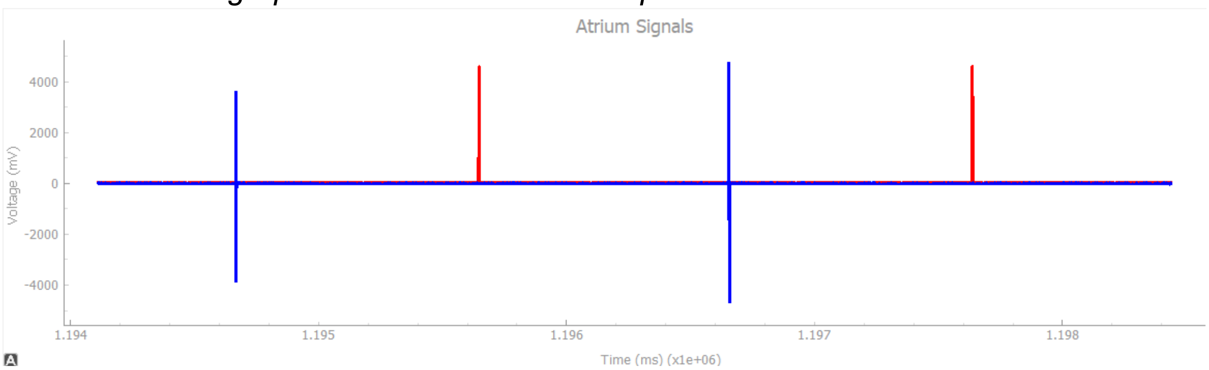
Chamber paced: Atrium
Chamber sensed: Atrium
Response to Sensing: Inhibited

Test Cases:

a) <u>Natural Atrium: **ON**, Pulse Width: **1ms** | Natural Ventricle: **OFF** | Heart Rate: **30bpm**</u>

At very low Heat Rate and low Pulse Width, pacemaker is supposed to generate pulse (because heart produces pulse every 2000ms, and pacemaker is supposed to maintain Heart rate of 60bpm which is pulse after every 1000ms).
As we can see from the graph below, our pacemaker provides a pulse after every 1000ms to bridge the gap.

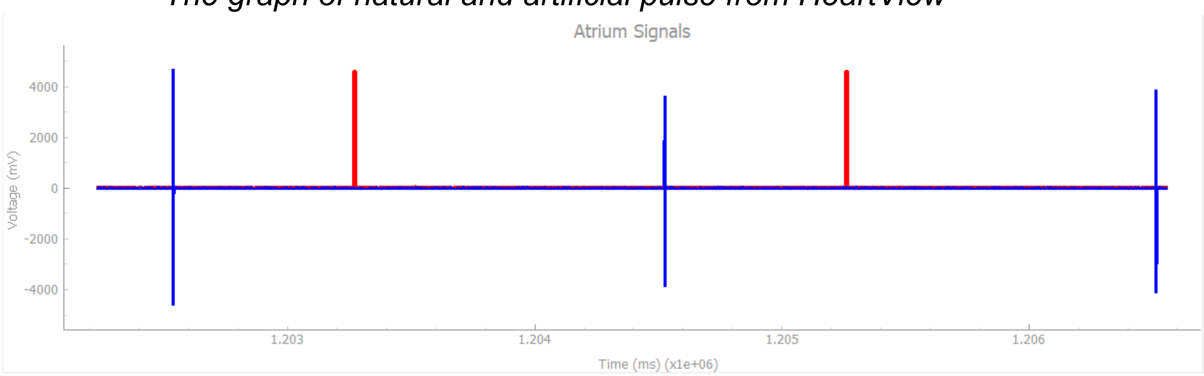
The graph of natural and artificial pulse from HeartView



b) <u>Natural Atrium: **ON**, Pulse Width: **10ms** | Natural Ventricle: **OFF** | Heart Rate: **30bpm**</u>

When we increase the pulse width to 10ms and keep hear rate same, still the gap between 2 consecutive pulses is more than 1000ms, so pacemaker is supposed to produce the pulse.
As we can see from the graph below, our pacemaker does the same, it provides the pulse to bridge the time gap.

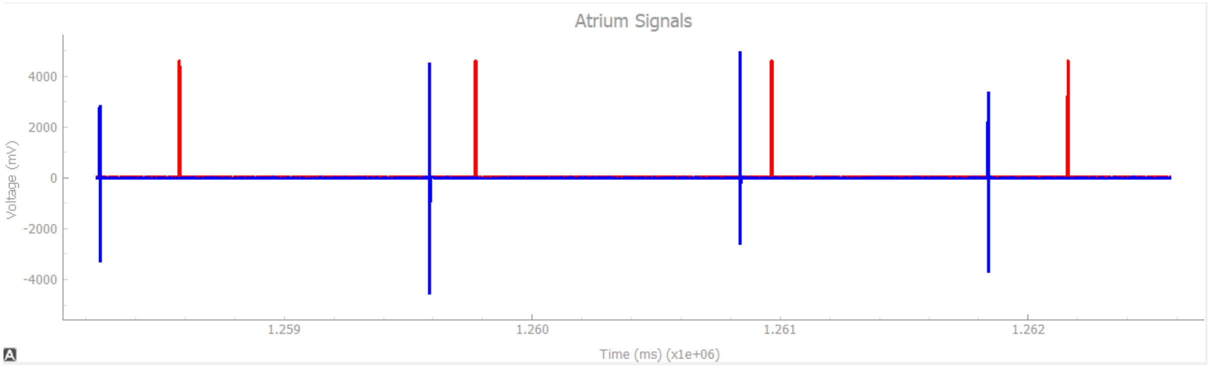
The graph of natural and artificial pulse from HeartView



c) <u>Natural Atrium: **ON**, Pulse Width: **1ms** | Natural Ventricle: **OFF** | Heart Rate: **50bpm**</u>

When our heart rate is just below the natural rate but pulse width is not big enough to reach the natural rate (i.e. 60bpm or pulse after every 1000ms), pacemaker is supposed t provide artificial pulse.
From the graph below, it is clear that our pacemaker takes care of the delay.

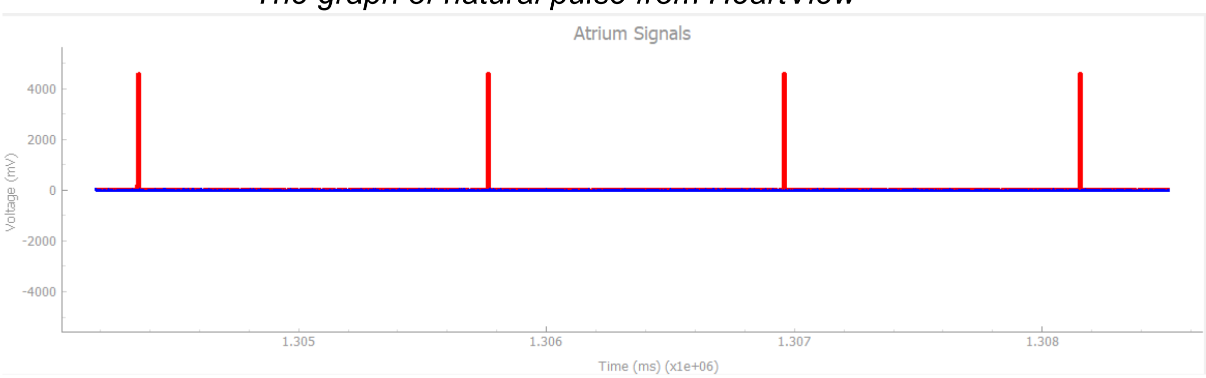
The graph of natural and artificial pulse from HeartView



d) <u>Natural Atrium: **ON**, Pulse Width: **10ms** | Natural Ventricle: **OFF** | Heart Rate: **50bpm**</u>

When the heart rate is below normal but pulse width is big enough to account for the gap, pacemaker is not supposed to provide any artificial pulse.
As we can see from the graph below, our pacemaker is not providing any additional pulse to the heart.

The graph of natural pulse from HeartView



6.4 VVI

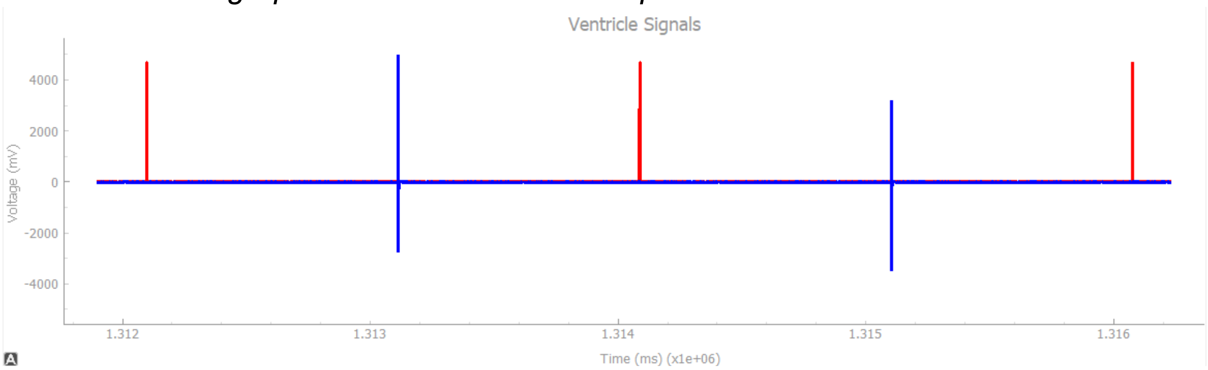
Chamber paced: Ventricle
Chamber sensed: Ventricle
Response to Sensing: Inhibited

Test Cases:

a) <u>Natural Atrium: **OFF** | Natural Ventricle: **ON**, Pulse Width: **1ms** | Heart Rate: **30bpm**</u>

At very low heart rate, pacemaker is expected to provide pulse at sufficient interval to maintain overall normal heart rate.
As we can see from graph below, our pacemaker provides artificial pulses whenever the time till last pulse is more than 1000ms, which helps in maintaining normal heart rate of 60bpm or pulse after every 1000ms.

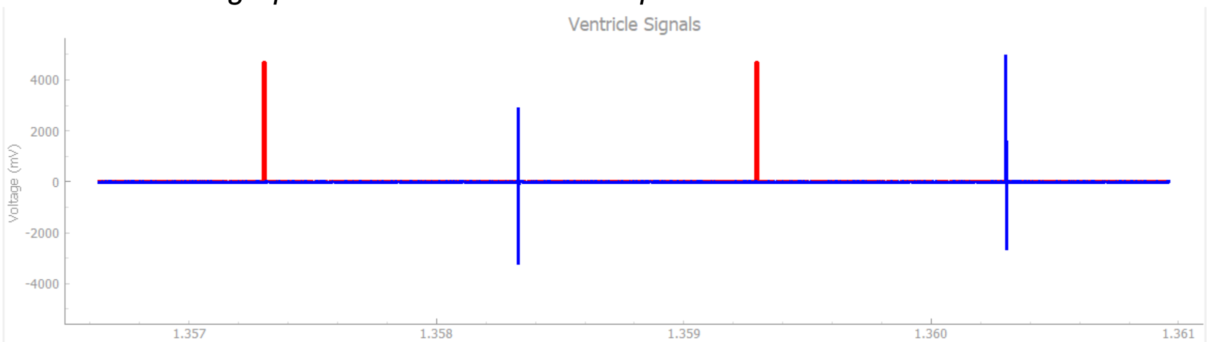
The graph of natural and artificial pulse from HeartView



b) <u>Natural Atrium: **OFF** | Natural Ventricle: **ON**, Pulse Width: **10ms** | Heart Rate: **30bpm**</u>

When the heart rate is low, high pulse width is not able to bridge the gap and pacemaker is supposed to provide pulses in order to make sure proper functioning of the heart.
From the graph below, it is clear that our pacemaker sends artificial pulses to the heart and maintains normal functioning.

The graph of natural and artificial pulse from HeartView

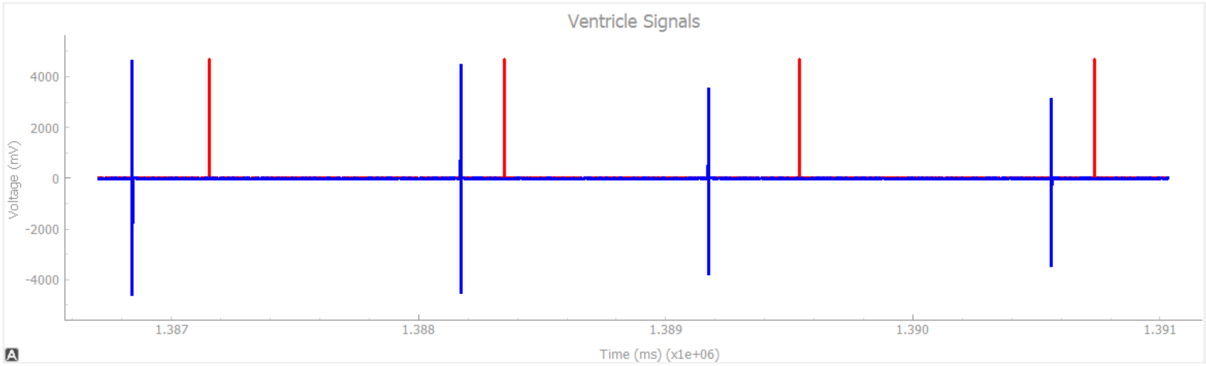


c) <u>Natural Atrium: **OFF** | Natural Ventricle: **ON**, Pulse Width: **1ms** | Heart Rate: **50bpm**</u>

When heart is beating just below normal rate but pulse width is not big enough to bridge the gap, pacemaker is expected to come into play and send pulses to the heart.

From the graph below, we can see that our pacemaker does exactly what is expected.

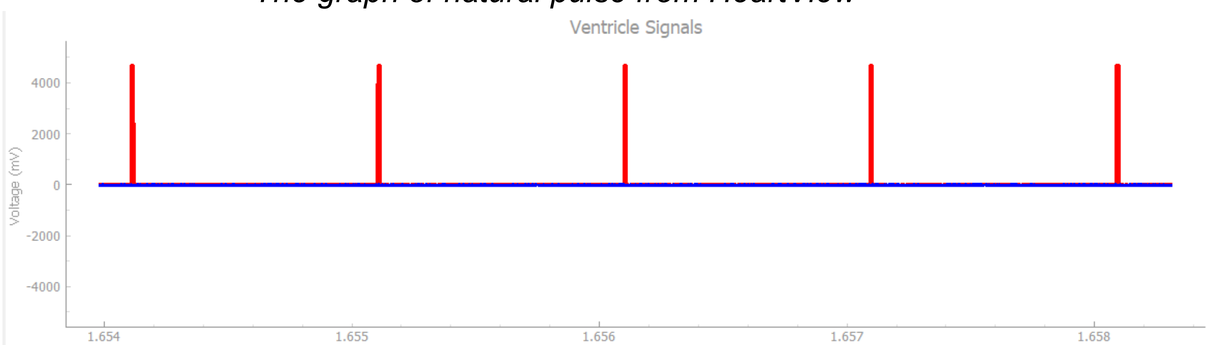
The graph of natural and artificial pulse from HeartView



d) <u>Natural Atrium: **OFF** | Natural Ventricle: **ON**, Pulse Width: **10ms** | Heart Rate: **58bpm**</u>

When heart rate is just below the normal and pulse width is wide enough to bridge the gap, pacemaker should not do anything.
As we can see from the graph below, our pacemaker if not producing any artificial pulses to the heart.

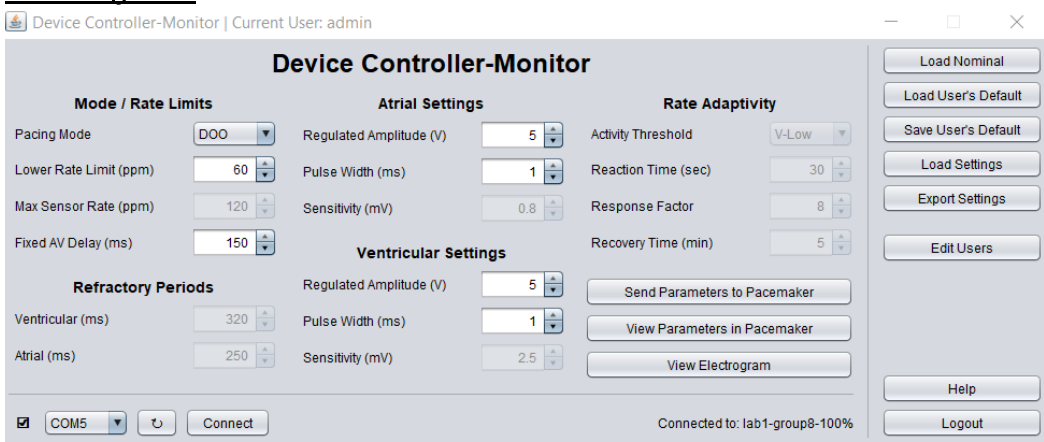
The graph of natural pulse from HeartView



6.5 DOO

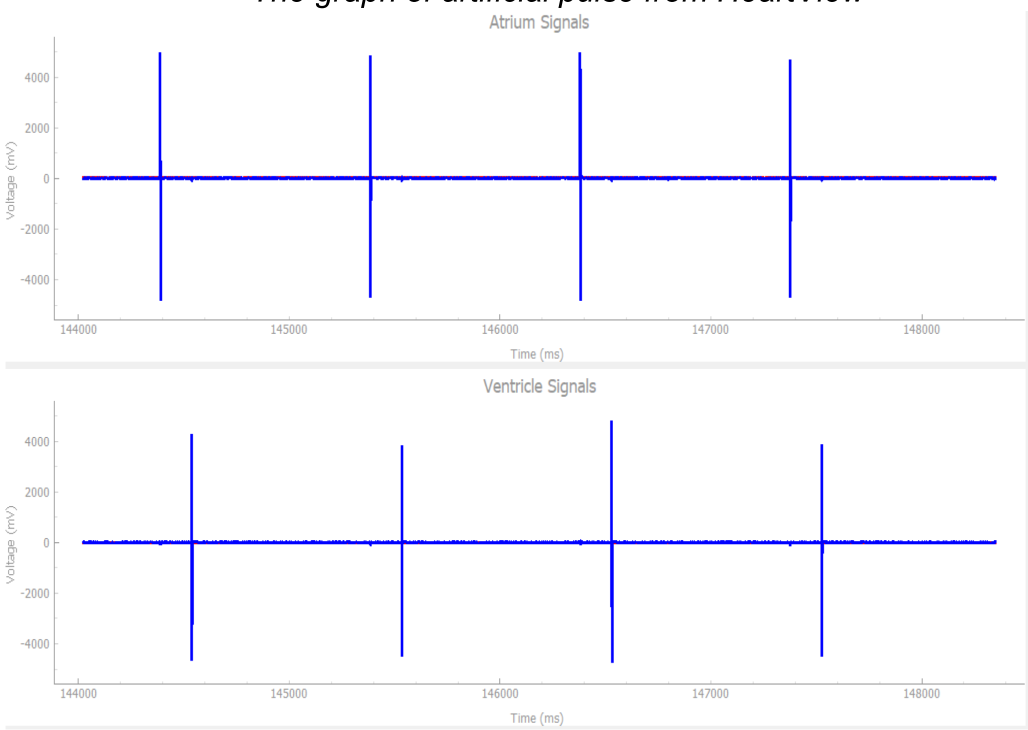
Chamber paced: Atrium and Ventricle
Chamber sensed: None
Response to Sensing: None
Rate Modulation
<u>Heartview signals</u>: Natural Atrium: **OFF** | Natural Ventricle: **OFF**

DCM signals:



In DOO mode also, as we are not sensing any chamber, only a single test case (when both atrium and ventricle are not working) can demonstrate correctness of our pacemaker.

The graph of artificial pulse from HeartView

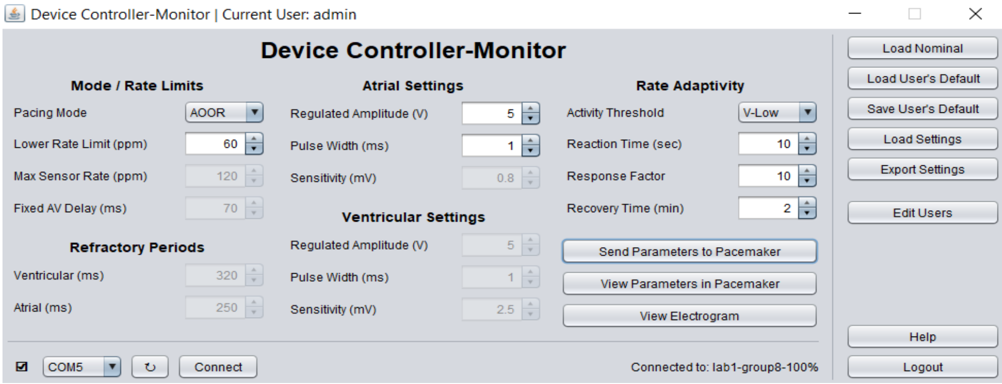


Pace to Ventricle and Atrium with LRL of 60 ppm and an AV delay of 150 ms

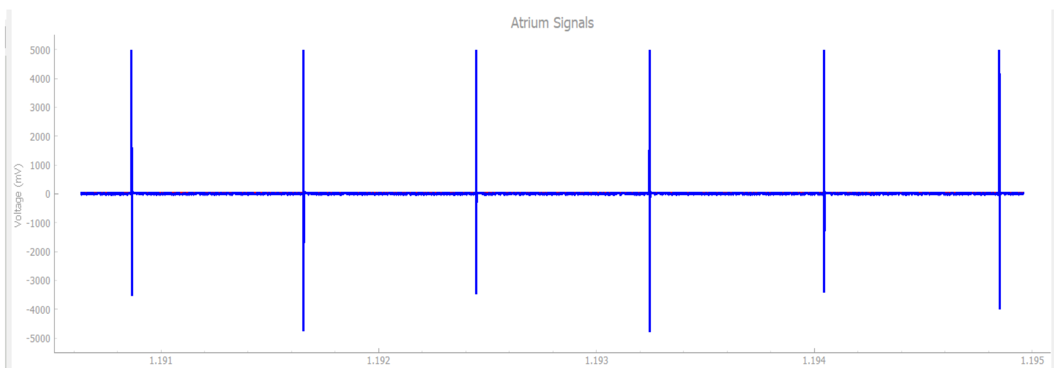
Result: Passed

6.6 AOOR

Chamber paced: Atrium
Chamber sensed: None
Response to Sensing: None
Rate Modulation
Heartview signals: Natural Atrium: **OFF** | Natural Ventricle: **OFF**

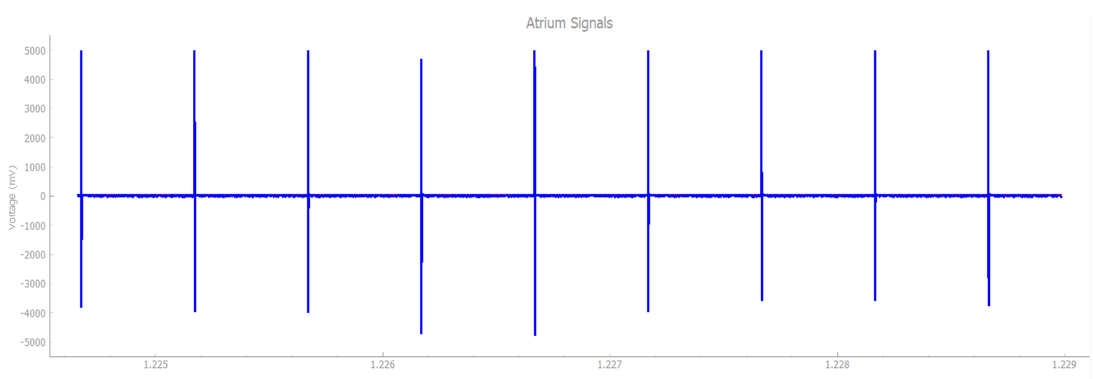


a) No Activity sensed



If no Activity is sensed above Threshold, Pace to Atrium with an LRL of 60 ppm

b) Activity sensed

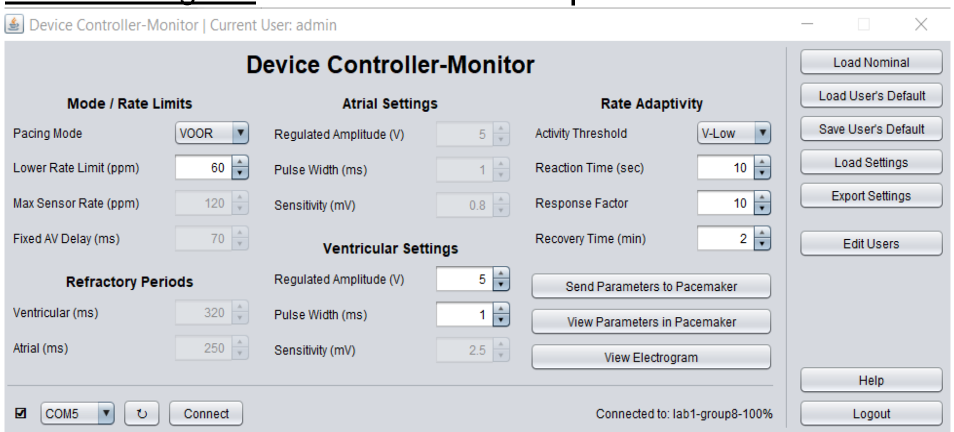


After sensing Activity above Threshold, increase LRL within a response time of 10 seconds and a recovery time of 2 minutes

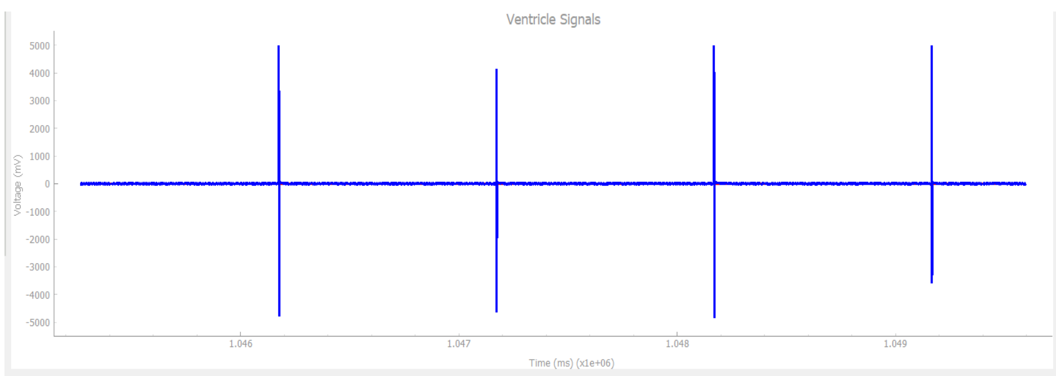
Result: Passed

6.7 VOOR

Chamber paced: Ventricle
Chamber sensed: None
Response to Sensing: None
Rate Modulation
<u>Heartview signals</u>: Natural Atrium: **OFF | **Natural Ventricle: **OFF**

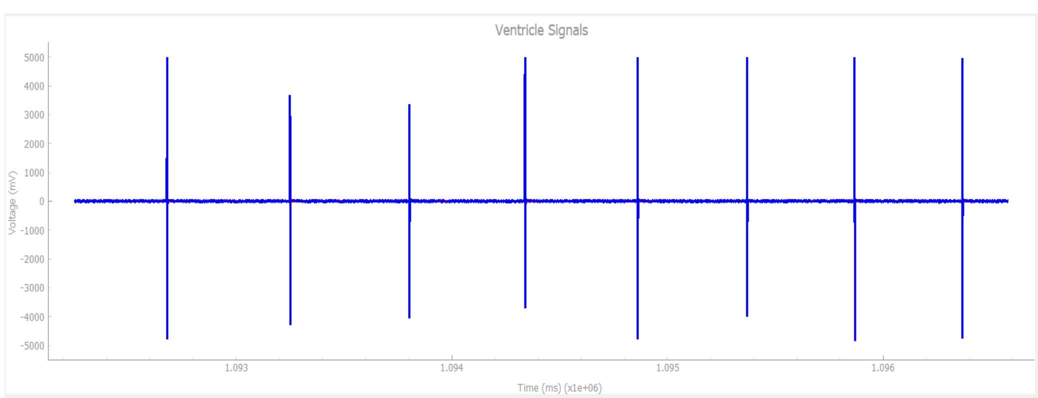


a) **<u>No Activity sensed</u>**



If no Activity is sensed above Threshold, Pace to Ventricle with LRL of 60 ppm

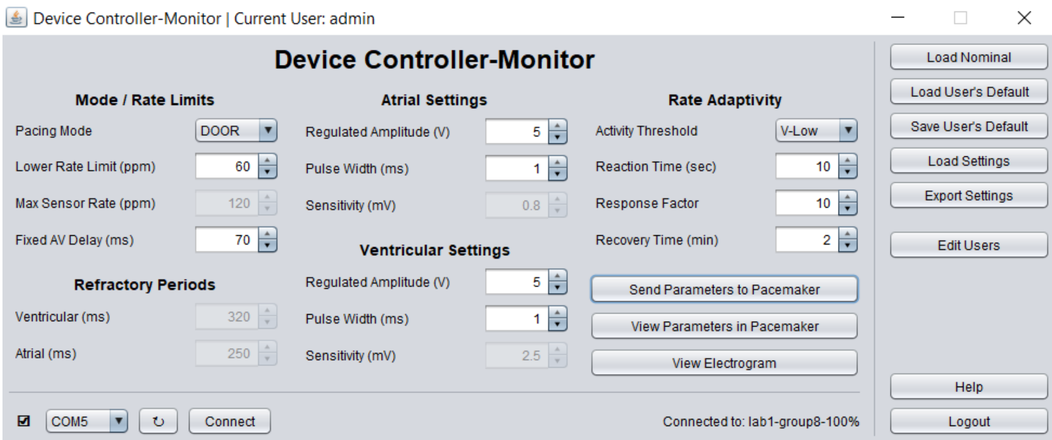
b) **<u>Activity Sensed</u>**



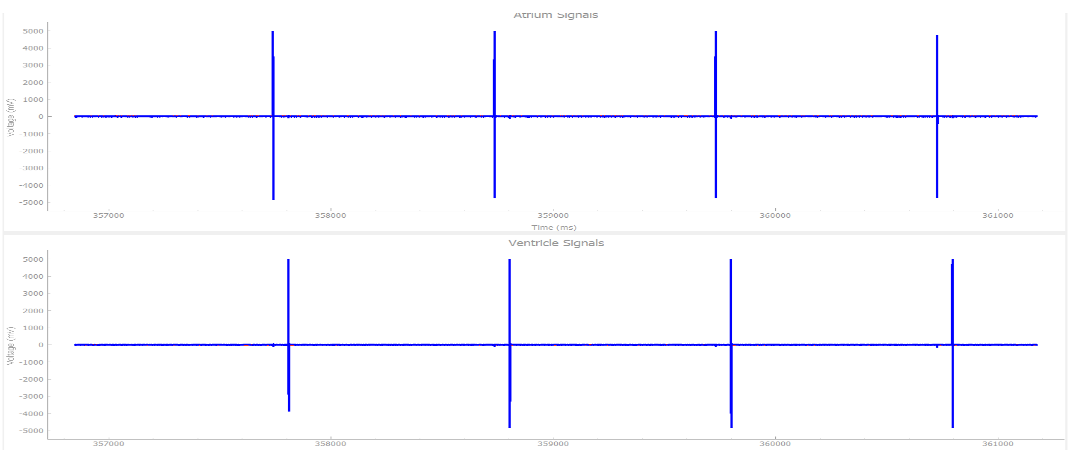
After sensing Activity above Threshold, increase LRL within a response time of 10 seconds and a recovery time of 2 minutes
Result: Passed

6.8 DOOR

Chamber paced: Atrium and Ventricle
Chamber sensed: None
Response to Sensing: None
Rate Modulation
Heartview signals: Natural Atrium: **OFF** | Natural Ventricle: **OFF**

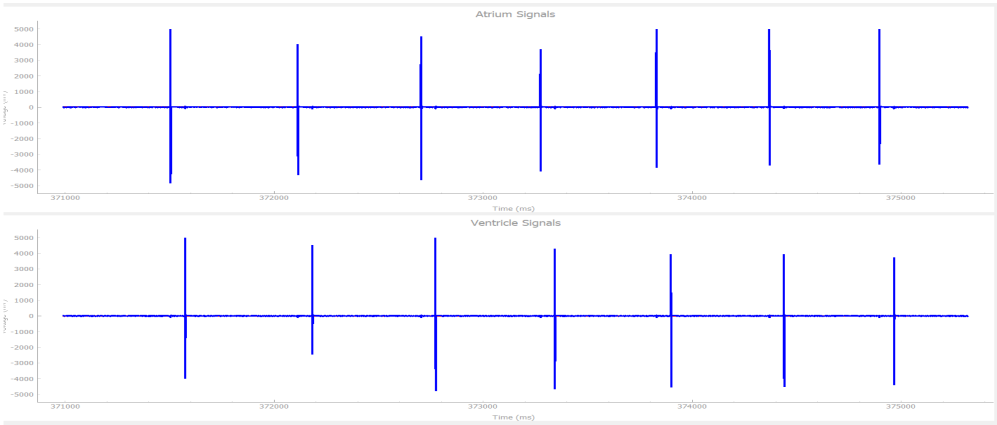


a) No Activity sensed



If no Activity is sensed above Threshold, Pace to Ventricle and Atrium with an LRL of 60 ppm and AV delay of 70 ms

b) Activity sensed



After sensing Activity above Threshold, increase LRL within a response time of 10 seconds and a recovery time of 2 minutes

Result: Passed

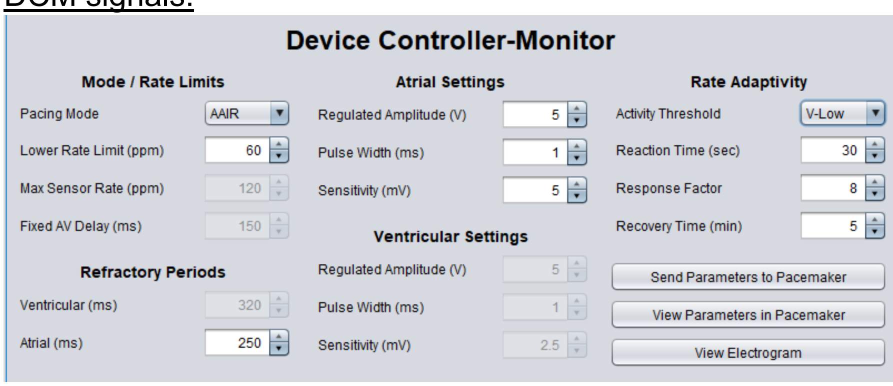
6.9 AAIR

Chamber paced: Atrium
Chamber sensed: Atrium
Response to Sensing: Inhibited
Rate Modulation

Test Cases:

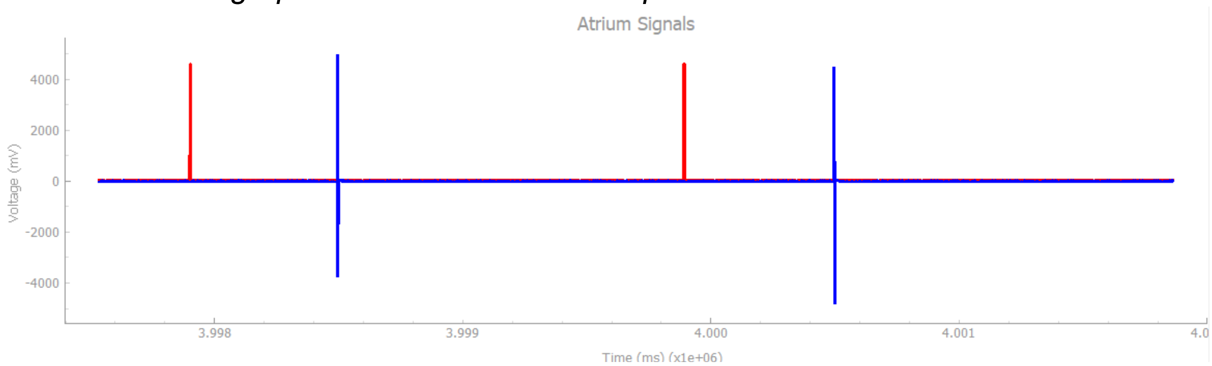
a) **No activity**
<u>Heartview signals</u>: Natural Atrium: **On |** PW: 1ms | Heart rate: 30Bpm

<u>DCM signals:</u>



<u>Explanation:</u> When we are operating on AAIR mode with no activity in pacemaker and heart rate is below normal, pacemaker is supposed to produce the pulse to bridge the gap. As we can see from graph below, our pacemaker does the same.

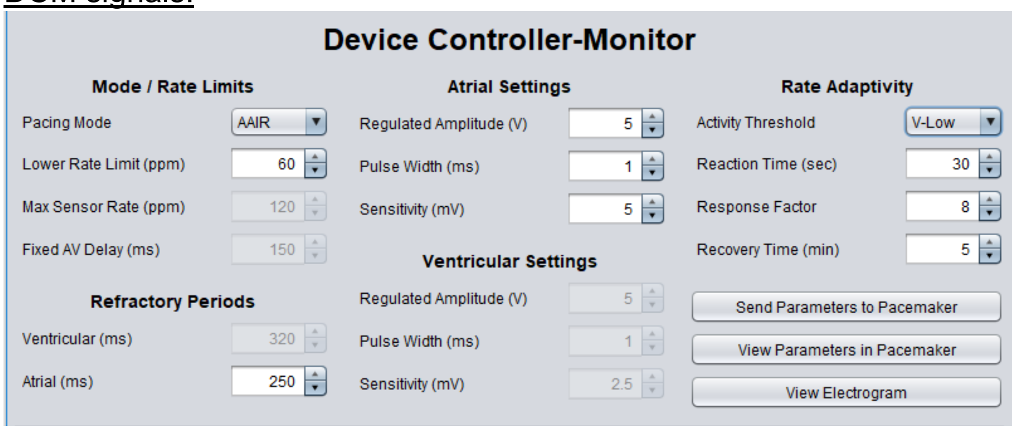
The graph of artificial and natural pulse from HeartView



b) **Physical activity**

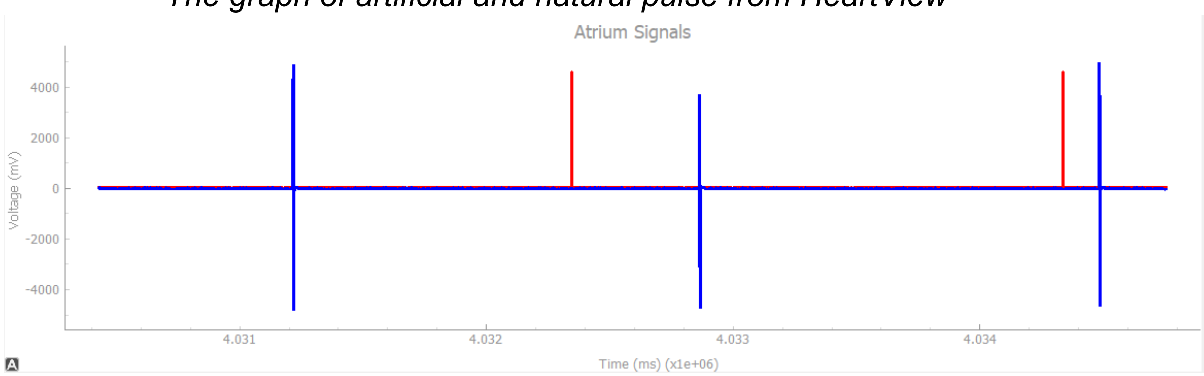
Heartview signals: Natural Atrium: **On |** PW: 1ms | Heart rate: 30Bpm

DCM signals:



Explanation: When there is some physical activity, our pacemaker produces more pulses than under normal conditions.

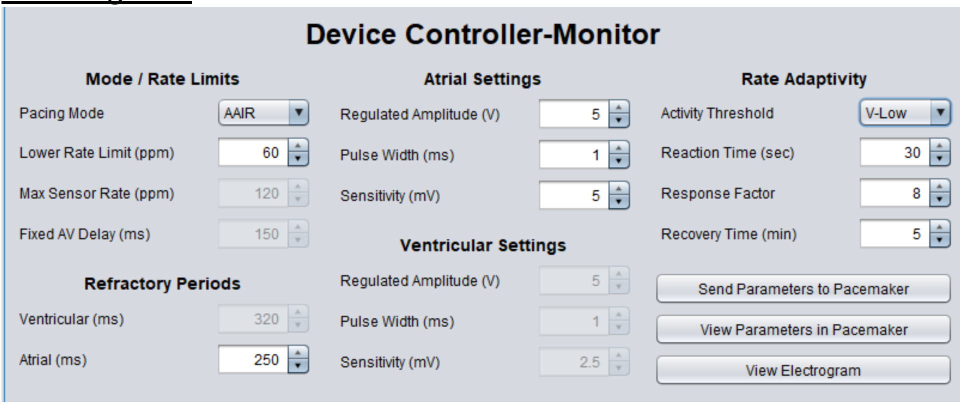
The graph of artificial and natural pulse from HeartView



c) **No activity**

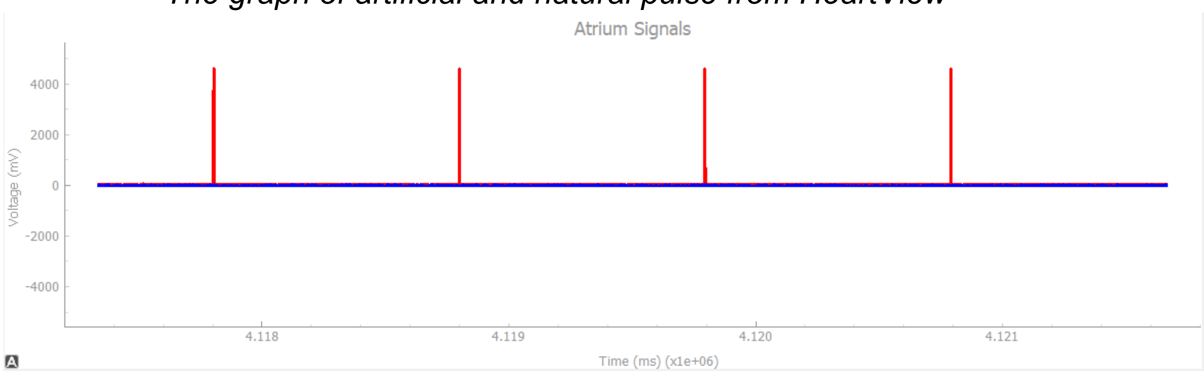
<u>Heartview signals</u>: Natural Atrium: **On |** PW: 1ms | Heart rate: 60Bpm

<u>DCM signals:</u>



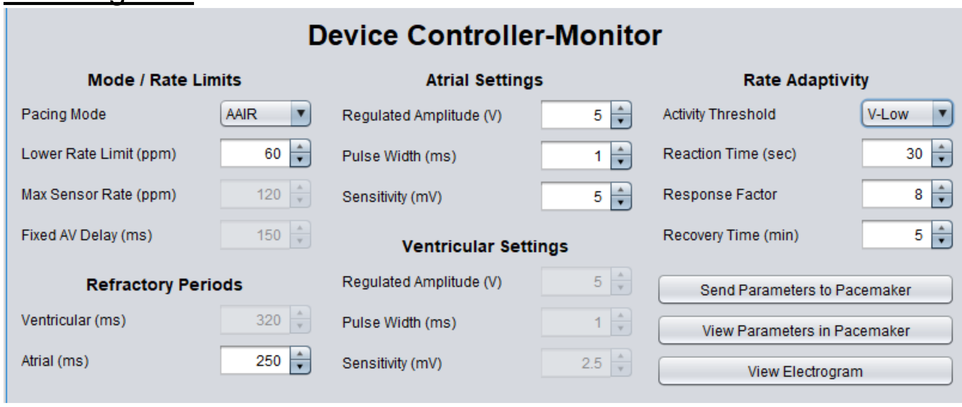
<u>Explanation:</u> When there is no physical activity and heart is beating at natural rate, pacemaker is not supposed to provide any additional pulse. Our pacemaker does the same which is clear from following graph.

The graph of artificial and natural pulse from HeartView



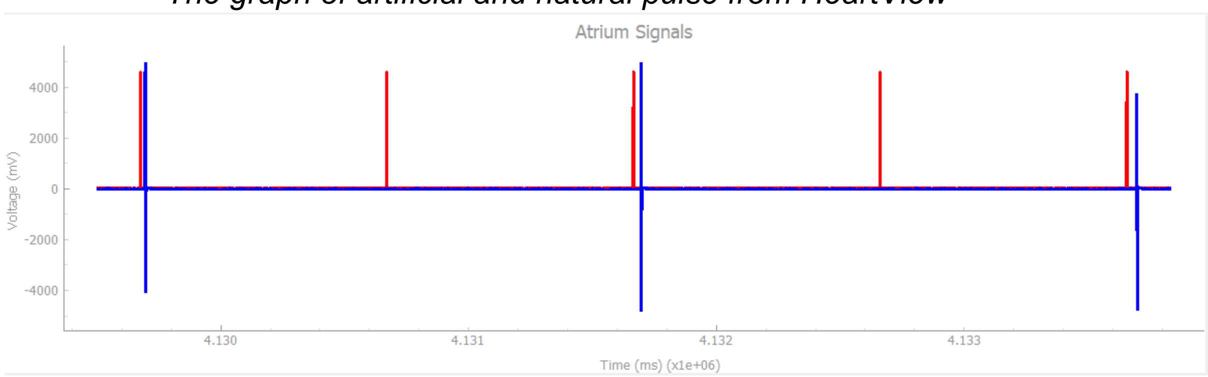
d) **Physical activity**
Heartview signals: Natural Atrium: **On |** PW: 1ms | Heart rate: 60Bpm

DCM signals:



Explanation: When there is some physical activity and heart is beating at regular rate, pacemaker should provide additional pulse to account for the physical activity. It is clear from the below graph that our pacemaker does exactly the same.

The graph of artificial and natural pulse from HeartView



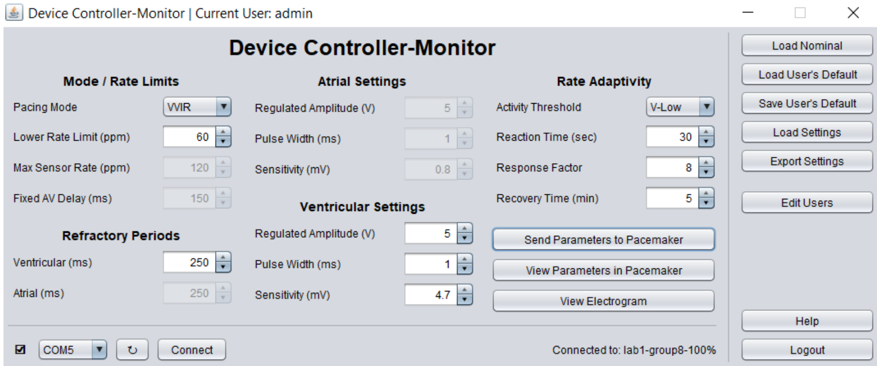
6.10 VVIR

Chamber paced: Ventricle
Chamber sensed: Ventricle
Response to Sensing: Inhibited
Rate Modulation

Test Cases:

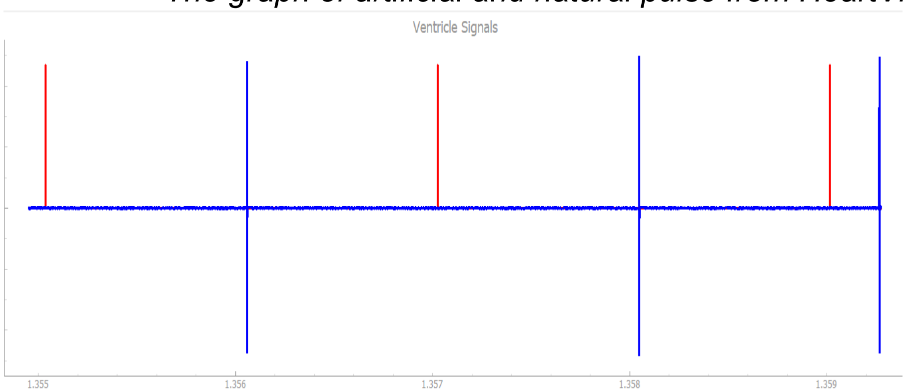
a) No activity
Heartview signals: Natural Ventricle: **On |** PW: 1ms | Heart rate: 30Bpm

DCM signals:



Explanation: When we are operating on VVIR mode with no activity in pacemaker and heart rate is below normal, pacemaker is supposed to produce the pulse to bridge the gap. As we can see from graph below, our pacemaker does the same.

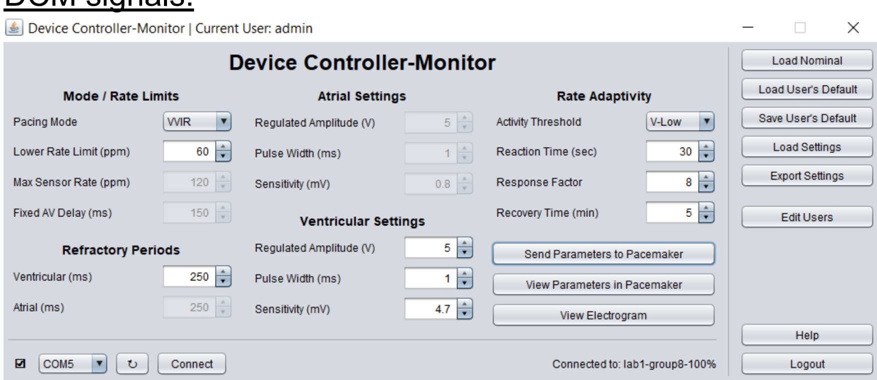
The graph of artificial and natural pulse from HeartView



b) **Physical activity**

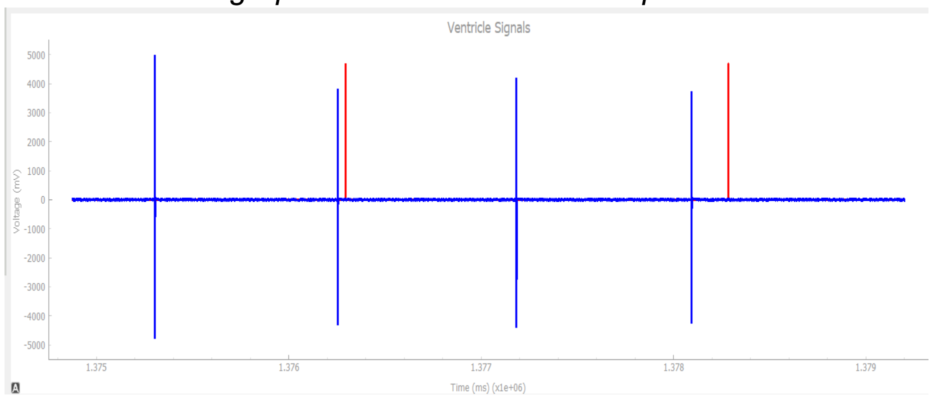
Heartview signals: Natural Ventricle: **On** | PW: 1ms | Heart rate: 30Bpm

DCM signals:



Explanation: When there is some physical activity, our pacemaker produces more pulses than under normal conditions.

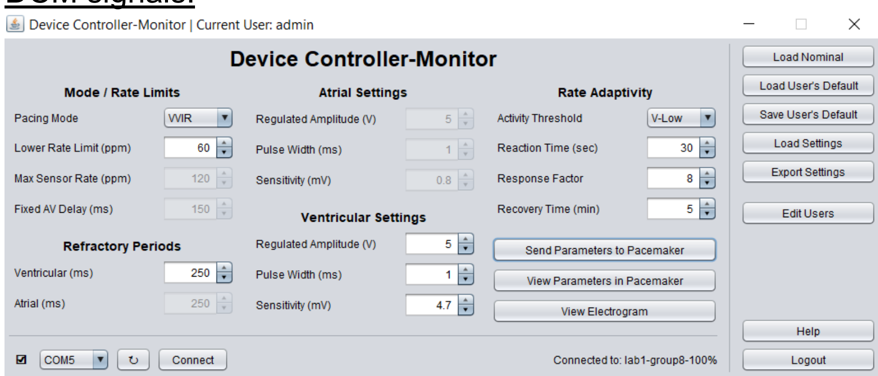
The graph of artificial and natural pulse from HeartView



c) No activity

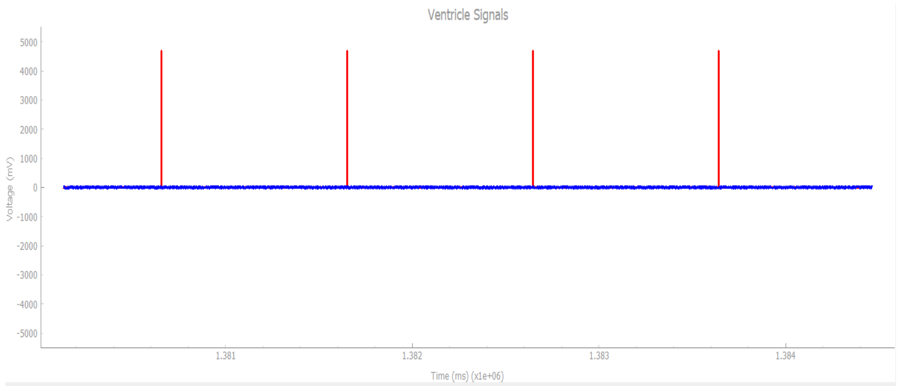
Heartview signals: Natural Ventricle: **On |** PW: 1ms | Heart rate: 60Bpm

DCM signals:



Explanation: When there is no physical activity and heart is beating at natural rate, pacemaker is not supposed to provide any additional pulse. Our pacemaker does the same which is clear from following graph.

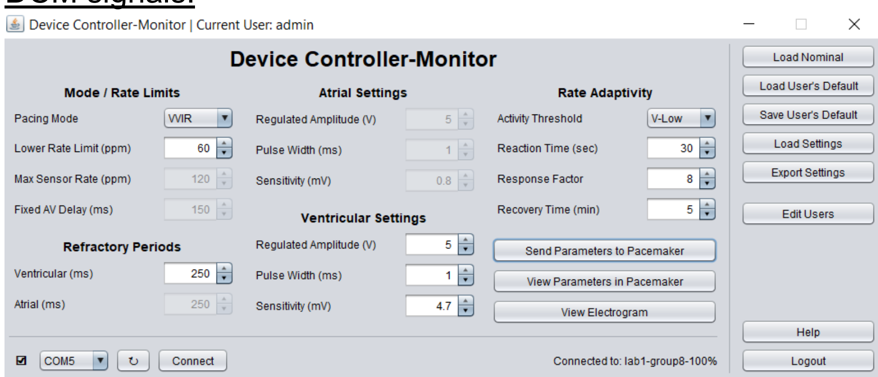
The graph of artificial and natural pulse from HeartView



d) Physical activity

Heartview signals: Natural Ventricle: **On |** PW: 1ms | Heart rate: 60Bpm

DCM signals:



Explanation: When there is some physical activity and heart is beating at regular rate, pacemaker should provide additional pulse to account for the physical activity. It is clear from the below graph that our pacemaker does exactly the same.

The graph of artificial and natural pulse from HeartView