Assignment 1, Part 1: Pacemaker modes

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# Introduction

The following documentation gives a concise and general description tailored to the end-user, of Part 1 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 State flow Implementation in MATLAB Simulink, which is used to simulate the 4 pacing/sensing modes (AOO, VOO, VVI, AAI) which are required for this early stage of the project. More pacing modes will be created in stage 2 of the project. A summary of these 4 modes will be introduced, but the documentation will provide a more in-depth analysis of each mode.

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

The implemented modes control the pacing of the heart by sending a 1 ms pulse start signal to the hardware controllers described in Part 3.

# Variables

## Measured

|  |  |  |  |
| --- | --- | --- | --- |
| **Name** | **Units/Type** | **Description** | **Range** |
| t | ms | Time since last pulse | – |
| h\_atr\_pulse\_detected | boolean | Pulse detected in atrium | {true, false} |
| h\_vent\_pulse\_detected | boolean | Pulse detected in ventricle | {true, false} |

## Constant

|  |  |  |  |
| --- | --- | --- | --- |
| **Name** | **Units/Type** | **Description** | **Range** |
| p\_mode | mode | Pacemaker operational mode | {AOO,VOO,AAI,VVI} |
| p\_lower\_rate\_limit | ms | Lowest allowable heart rate | 343–2000 ± 8 ms |
| p\_upper\_rate\_limit | ms | Highest allowable heart rate | 343–1200 ± 8ms |
| p\_vrp | ms | Ventricular Refractory Period | 150–500 ± 8 ms |
| p\_arp | ms | Atrial Refractory Period | 150–500 ± 8 ms |
| p\_hysteresis\_enable | boolean | Hysteresis mode enabled | {true, false} |
| p\_hysteresis\_limit | ms | Hysteresis rate limit | 343–2000 ± 8 ms |
| p\_rate\_smoothing\_enable | boolean | Rate smoothing enabled | {true, false} |
| p\_rate\_smoothing\_down | percent | Maximum allowable pacing rate decrease | 3–25 ± 1% |
| p\_rate\_smoothing\_up | percent | Maximum allowable pacing rate increase | 3–25 ± 1% |

## Controlled

|  |  |  |  |
| --- | --- | --- | --- |
| **Name** | **Units/Type** | **Description** | **Range** |
| A\_pace\_start | boolean | Commence atrial pulse | {true, false} |
| V\_pace\_start | boolean | Commence ventricular pulse | {true, false} |

## Internal

|  |  |  |  |
| --- | --- | --- | --- |
| **Name** | **Units/Type** | **Description** | **Range** |
| i\_last\_period | ms | Last period between pulses | – |

# Modes

## **AOO**

### Description

In AOO mode, the atrium is paced at the rate defined by p\_lower\_rate\_limit. The upper rate limit is not used so it is not included in the design.

### Variables

#### Measured

|  |  |  |
| --- | --- | --- |
| **Name** | **Abbreviation** | **Reference** |
| t | t | 2.1 |

#### Constant

|  |  |  |
| --- | --- | --- |
| **Name** | **Abbreviation** | **Reference** |
| p\_lower\_rate\_limit | LRL | 2.2 |
| p\_upper\_rate\_limit | URL | 2.2 |

#### Controlled

|  |  |  |
| --- | --- | --- |
| **Name** | **Abbreviation** | **Reference** |
| A\_pace\_start | PS | 2.3 |

### Requirements

|  |  |
| --- | --- |
| **t** | **Pace** |
| t<LRL | False |
| t=LRL | True |

### Future Changes

There are no foreseeable changes to this mode.

### Stateflow Screenshot

Diagram

Description automatically generated

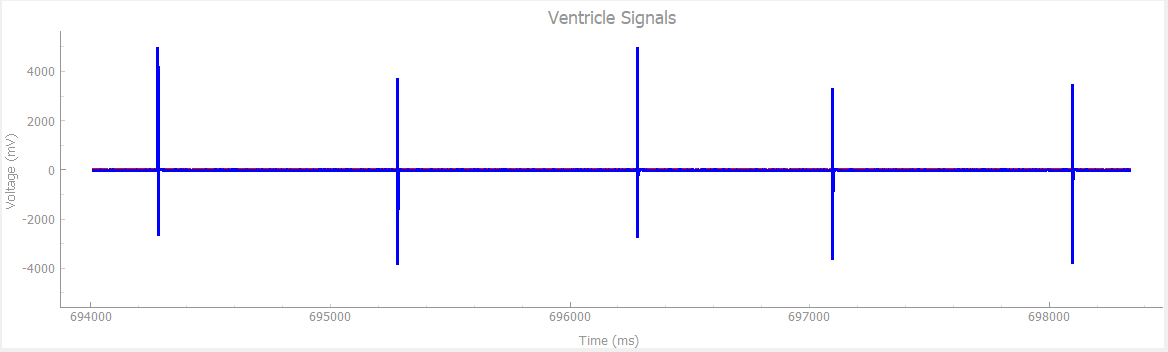
### Testing

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| ***AOO Testing Outcomes*** | | | | |
| **Test Case** | | **Expected Result** | **Actual Result** | **Pass/Fail** |
| **Natural Atrium** | **Natural Ventricle** |
| OFF | OFF | No response to sensing | No response to sensing | Pass |

1. Natural Atrium: **OFF |** Natural Ventricle: **OFF**

In AOO 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*



## **VOO**

### Description

In VOO mode, the ventricle is paced at the rate defined by p\_lower\_rate\_limit. The upper rate limit is not used so it is not included in the design.

### Variables

#### Measured

|  |  |  |
| --- | --- | --- |
| **Name** | **Abbreviation** | **Reference** |
| t | t | 2.1 |

#### Constant

|  |  |  |
| --- | --- | --- |
| **Name** | **Abbreviation** | **Reference** |
| p\_lower\_rate\_limit | LRL | 2.2 |

#### Controlled

|  |  |  |
| --- | --- | --- |
| **Name** | **Abbreviation** | **Reference** |
| V\_pace\_start | PS | 2.3 |

### Requirements

|  |  |
| --- | --- |
| **t** | **Pace** |
| t<LRL | False |
| t=LRL | True |

### Future Changes

There are no foreseeable changes to this mode.

### Stateflow Screenshot

Diagram

Description automatically generated

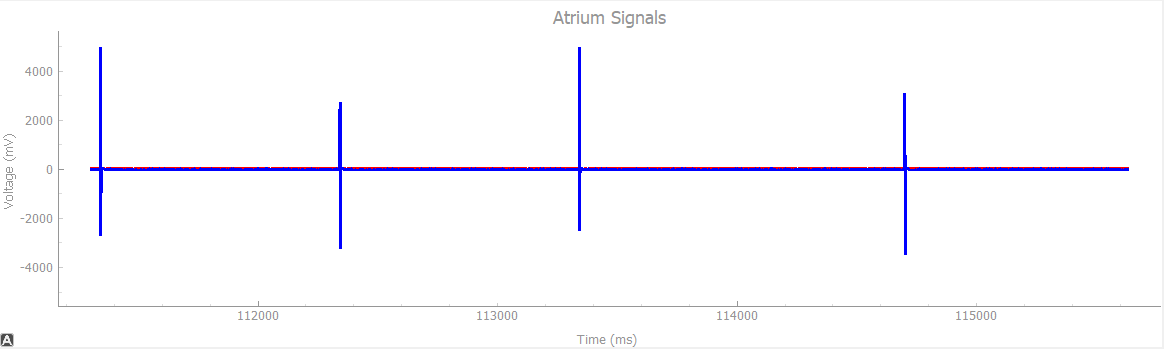
### Testing

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| ***VOO Testing Outcomes*** | | | | |
| **Test Case** | | **Expected Result** | **Actual Result** | **Pass/Fail** |
| **Natural Atrium** | **Natural Ventricle** |
| OFF | OFF | No response to sensing | No response to sensing | Pass |

1. Natural Atrium: **OFF |** Natural Ventricle: **OFF**

In VOO 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*



## **AAI**

### Description

In AAI mode, the atrium is paced at the rate defined by p\_lower\_rate\_limit unless a spontaneous pulse is detected. Spontaneous pulses that occur within the atrial refractory period after a natural or spontaneous pulse are not processed.

If hysteresis is enabled and the previous pulse was spontaneous, the pacing rate is decreased to p\_hysteresis\_limit.

If rate smoothing is enabled, the last period between pulses is recorded and the current heart rate is calculated. The pulsing rate trends towards either p\_lower\_rate\_limit or p\_hysteresis\_limit, decreasing by at most the amount defined by p\_rate\_smoothing\_down and increasing by at most the amount defined by p\_rate\_smoothing\_up.

In all cases the pacemaker will never pace faster than the rate defined by p\_upper\_rate\_limit.

The documentation does not make clear the purpose of post-ventricular atrial refractory period, so it is not included in the design.

### Variables

#### Measured

|  |  |  |
| --- | --- | --- |
| **Name** | **Abbreviation** | **Reference** |
| t | t | 2.1 |
| h\_atr\_pulse\_detected | PD | 2.1 |

#### Constant

|  |  |  |
| --- | --- | --- |
| **Name** | **Abbreviation** | **Reference** |
| p\_lower\_rate\_limit | LRL | 2.2 |
| p\_upper\_rate\_limit | URL | 2.2 |
| p\_arp | ARP | 2.2 |
| p\_hysteresis\_enable | HE | 2.2 |
| p\_hysteresis\_limit | HL | 2.2 |
| p\_rate\_smoothing\_enable | RSE | 2.2 |
| p\_rate\_smoothing\_down | RSD | 2.2 |
| p\_rate\_smoothing\_up | RSU | 2.2 |

#### Controlled

|  |  |  |
| --- | --- | --- |
| **Name** | **Abbreviation** | **Reference** |
| A\_pace\_start | PS | 2.3 |

#### Internal

|  |  |  |
| --- | --- | --- |
| **Name** | **Abbreviation** | **Reference** |
| i\_last\_period | LP | 2.4 |

### Requirements

#### Hysteresis and Rate Smoothing Disabled

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Last Pulse Type | Last Period | t | Spontaneous pulse resets timer | PS |
| X | X |  | false | false |
|  | true | false |
|  | true |

#### Hysteresis Disabled and Rate Smoothing Enabled

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Last Pulse Type | Last Period | t | Spontaneous pulse resets timer | PS |
| X | X |  | false | false |
| X |  | true | false |
|  |  | true |
|  |  | false |
|  | true |
|  |  | false |
|  | true |

#### Hysteresis Enabled and Rate Smoothing Disabled

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Last Pulse Type | Last Period | t | Spontaneous pulse resets timer | PS |
| X | X |  | false | false |
|  | true | false |
| Sensed |  | false |
|  | true |
| Paced |  | false |
|  | true |

#### Hysteresis and Rate Smoothing Enabled

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Last Pulse Type | Last Period | t | Spontaneous pulse resets timer | PS |
| X | X |  | false | false |
| X |  | true | false |
| Sensed |  |  | true |
|  |  | false |
|  | true |
|  |  | false |
|  | true |
| Paced |  |  | false |
|  | true |
|  |  | false |
|  | true |
|  |  | false |
|  | true |

### State Transitions

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Next State  Current State | INITIAL | PACED | SENSED | UPPER RATE LIMIT | LOWER RATE LIMIT | HYSTERESIS LIMIT | RATE SMOOTHING DOWN | RATE SMOOTHING UP |
| INITIAL | – | HE = true  t = HL  **or**  HE = false  t = LRL | PD = true | – | – | – | – | – |
| PACED | – | – | – | – | RSE = true  LP ≥ LRL(1-RSD)  LP ≤ LRL(1+RSU)  **or**  RSE = false | – | RSE = true  LP < LRL(1-RSD) | RSE = true  LP > LRL(1+RSU) |
| SENSED | – | – | – | RSE = true  LP≤URL(1-RSD) | HE = false  RSE = false  **or**  HE = false  RSE = true  LP≥ LRL(1-RSD) | HE = true  RSE = true  LP≥HL(1-RSD)  **or**  HE = true  RSE = false | HE = true  RSE = true  LP > URL(1-RSD)  LP < HL(1-RSD)  **or**  HE = false  RSE = true  LP > URL(1-RSD)  LP < LRL(1-RSD) | – |
| UPPER RATE LIMIT | – | t = URL | PD = true | – | – | – | – | – |
| LOWER RATE LIMIT | – | t = LRL | PD = true | – | – | – | – | – |
| HYSTERESIS LIMIT | – | t = HL | PD = true | – | – | – | – | – |
| RATE SMOOTHING DOWN | – | t=LP(1+RSD) | PD = true | – | – | – | – | – |
| RATE SMOOTHING UP | – | t=LP(1-RSD) | PD = true | – | – | – | – | – |

### State details

|  |  |
| --- | --- |
| **State** | **Description** |
| INITIAL | If hysteresis is enabled, pacemaker listens for sensed pulses until p\_hysteresis\_limit before pacing.  If hysteresis is not enabled, pacemaker listens for sensed until p\_lower\_rate\_limit before pacing. |
| PACED | Sends a 1 ms pulse on A\_pace\_start and waits for the duration of p\_arp |
| SENSED | Waits for the duration of p\_arp |
| UPPER RATE LIMIT | Listens for sensed pulses until p\_upper\_rate\_limit |
| LOWER RATE LIMIT | Listens for sensed pulses until p\_lower\_rate\_limit |
| HYSTERESIS LIMIT | Listens for sensed pulses until p\_hysteresis\_limit |
| RATE SMOOTHING DOWN | Listens for sensed pulses until limit defined by maximum allowable rate decrease |
| RATE SMOOTHING UP | Listens for sensed pulsed until limit defined by maximum allowable rate increase |

### Future changes

There are no foreseeable changes to this mode.

### Stateflow Screenshot

Diagram

Description automatically generated

### Testing

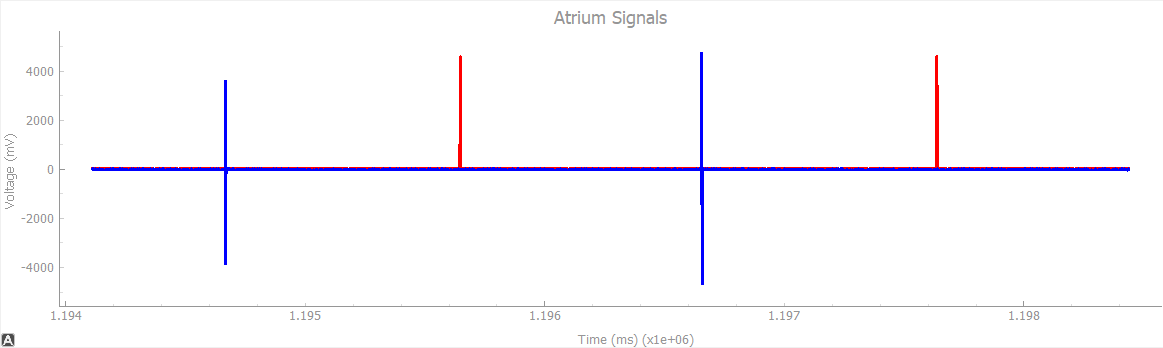
|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| ***AAI Testing outcomes*** | | | | | | |
| **Test Case** | | | | **Expected Result** | **Actual Result** | **Pass/Fail** |
| **Natural Atrium** | **Natural Ventricle** | **Heart Rate (bpm)** | **Pulse width (ms)** |
| ON | OFF | 30 | 1 | Pulse provided pulse every 1000ms | Pulse provided pulse every 1000ms | Pass |
| ON | OFF | 30 | 10 | Produce pulse in between every gap larger than 1000ms | Produce pulse in between every gap larger than 1000ms | Pass |
| ON | OFF | 50 | 1 | Provides pulse to account for delay | Provides pulse to account for delay | Pass |
| ON | OFF | 50 | 10 | No artificial pulse provided | No artificial pulse provided | Pass |

1. Natural Atrium: **ON**, Pulse Width: **1ms** |Natural Ventricle: **OFF** | Heart Rate: **30bpm**

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 Hear 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*

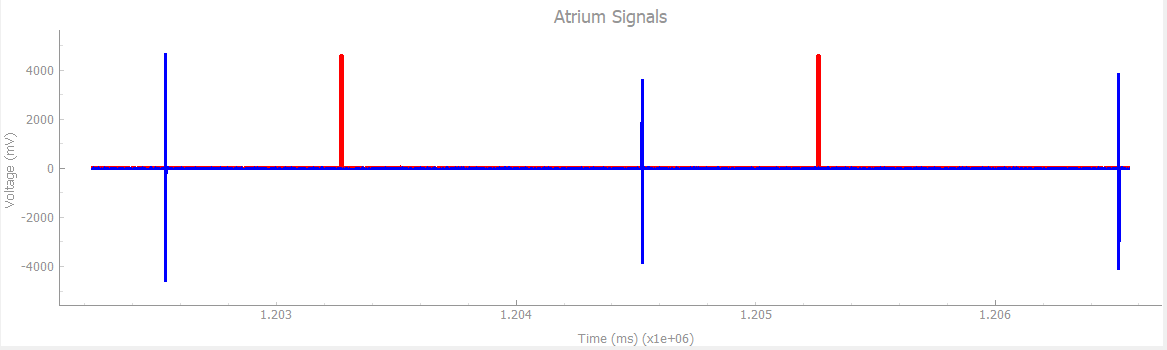


1. Natural Atrium: **ON**, Pulse Width: **10ms** |Natural Ventricle: **OFF** | Heart Rate: **30bpm**

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*

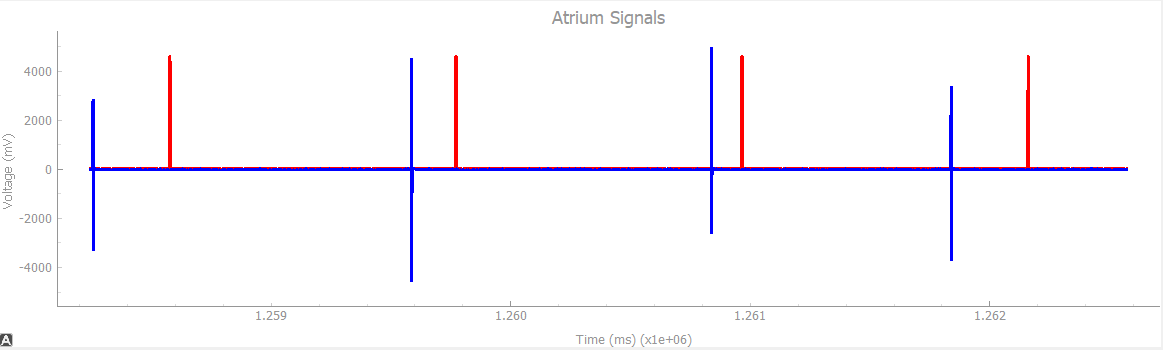


1. Natural Atrium: **ON**, Pulse Width: **1ms** |Natural Ventricle: **OFF** | Heart Rate: **50bpm**

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*

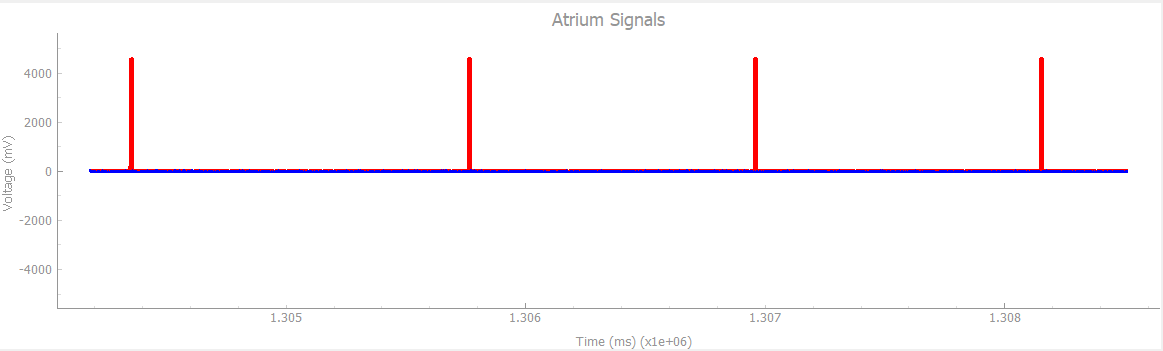


1. Natural Atrium: **ON**, Pulse Width: **10ms** |Natural Ventricle: **OFF** | Heart Rate: **50bpm**

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*



## **VVI**

### Description

In VVI mode, the ventricle is paced at the rate defined by p\_lower\_rate\_limit unless a spontaneous pulse is detected. Spontaneous pulses that occur within the ventricular refractory period after a natural or spontaneous pulse are not processed.

If hysteresis is enabled and the previous pulse was spontaneous, the pacing rate is decreased to p\_hysteresis\_limit.

If rate smoothing is enabled, the last period between pulses is recorded and the current heart rate is calculated. The pulsing rate trends towards either p\_lower\_rate\_limit or p\_hysteresis\_limit, decreasing by at most the amount defined by p\_rate\_smoothing\_down and increasing by at most the amount defined by p\_rate\_smoothing\_up.

In all cases the pacemaker will never pace faster than the rate defined by p\_upper\_rate\_limit.

### Variables

#### Measured

|  |  |  |
| --- | --- | --- |
| **Name** | **Abbreviation** | **Reference** |
| t | t | 2.1 |
| h\_vent\_pulse\_detected | PD | 2.1 |

#### Constant

|  |  |  |
| --- | --- | --- |
| **Name** | **Abbreviation** | **Reference** |
| p\_lower\_rate\_limit | LRL | 2.2 |
| p\_upper\_rate\_limit | URL | 2.2 |
| p\_vrp | VRP | 2.2 |
| p\_hysteresis\_enable | HE | 2.2 |
| p\_hysteresis\_limit | HL | 2.2 |
| p\_rate\_smoothing\_enable | RSE | 2.2 |
| p\_rate\_smoothing\_down | RSD | 2.2 |
| p\_rate\_smoothing\_up | RSU | 2.2 |

#### Controlled

|  |  |  |
| --- | --- | --- |
| **Name** | **Abbreviation** | **Reference** |
| V\_pace\_start | PS | 2.3 |

#### Internal

|  |  |  |
| --- | --- | --- |
| **Name** | **Abbreviation** | **Reference** |
| i\_last\_period | LP | 2.4 |

### Initial Values

V\_pace\_start = false

|  |  |
| --- | --- |
| **p\_hysteresis\_enable** | **i\_last\_period** |
| true | p\_hysteresis\_limit |
| false | p\_lower\_rate\_limit |

### Requirements

#### Hysteresis and Rate Smoothing Disabled

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Last Pulse Type | Last Period | t | Spontaneous pulse resets timer | PS |
| X | X |  | false | false |
|  | true | false |
|  | true |

#### Hysteresis Disabled and Rate Smoothing Enabled

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Last Pulse Type | Last Period | t | Spontaneous pulse resets timer | PS |
| X | X |  | false | false |
| X |  | true | false |
|  |  | true |
|  |  | false |
|  | true |
|  |  | false |
|  | true |

#### Hysteresis Enabled and Rate Smoothing Disabled

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Last Pulse Type | Last Period | t | Spontaneous pulse resets timer | PS |
| X | X |  | false | false |
|  | true | false |
| Sensed |  | false |
|  | true |
| Paced |  | false |
|  | true |

#### Hysteresis and Rate Smoothing Enabled

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Last Pulse Type | Last Period | t | Spontaneous pulse resets timer | PS |
| X | X |  | false | false |
| X |  | true | false |
| Sensed |  |  | true |
|  |  | false |
|  | true |
|  |  | false |
|  | true |
| Paced |  |  | false |
|  | true |
|  |  | false |
|  | true |
|  |  | false |
|  | true |

### State Transitions

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Next State  Current State | INITIAL | PACED | SENSED | UPPER RATE LIMIT | LOWER RATE LIMIT | HYSTERESIS LIMIT | RATE SMOOTHING DOWN | RATE SMOOTHING UP |
| INITIAL | – | HE = true  t = HL  **or**  HE = false  t = LRL | PD = true | – | – | – | – | – |
| PACED | – | – | – | – | RSE = true  LP ≥ LRL(1-RSD)  LP ≤ LRL(1+RSU)  **or**  RSE = false | – | RSE = true  LP < LRL(1-RSD) | RSE = true  LP > LRL(1+RSU) |
| SENSED | – | – | – | RSE = true  LP≤URL(1-RSD) | HE = false  RSE = false  **or**  HE = false  RSE = true  LP≥ LRL(1-RSD) | HE = true  RSE = true  LP≥HL(1-RSD)  **or**  HE = true  RSE = false | HE = true  RSE = true  LP > URL(1-RSD)  LP < HL(1-RSD)  **or**  HE = false  RSE = true  LP > URL(1-RSD)  LP < LRL(1-RSD) | – |
| UPPER RATE LIMIT | – | t = URL | PD = true | – | – | – | – | – |
| LOWER RATE LIMIT | – | t = LRL | PD = true | – | – | – | – | – |
| HYSTERESIS LIMIT | – | t = HL | PD = true | – | – | – | – | – |
| RATE SMOOTHING DOWN | – | t=LP(1+RSD) | PD = true | – | – | – | – | – |
| RATE SMOOTHING UP | – | t=LP(1-RSD) | PD = true | – | – | – | – | – |

### State details

|  |  |
| --- | --- |
| **State** | **Description** |
| INITIAL | If hysteresis is enabled, pacemaker listens for sensed pulses until p\_hysteresis\_limit before pacing.  If hysteresis is not enabled, pacemaker listens for sensed until p\_lower\_rate\_limit before pacing. |
| PACED | Sends a 1 ms pulse on V\_pace\_start and waits for the duration of p\_vrp |
| SENSED | Waits for the duration of p\_vrp |
| UPPER RATE LIMIT | Listens for sensed pulses until p\_upper\_rate\_limit |
| LOWER RATE LIMIT | Listens for sensed pulses until p\_lower\_rate\_limit |
| HYSTERESIS LIMIT | Listens for sensed pulses until p\_hysteresis\_limit |
| RATE SMOOTHING DOWN | Listens for sensed pulses until limit defined by maximum allowable rate decrease |
| RATE SMOOTHING UP | Listens for sensed pulsed until limit defined by maximum allowable rate increase |

### Future changes

There are no foreseeable changes to this mode.

### Stateflow Screenshot

Diagram, schematic

Description automatically generated

### Testing

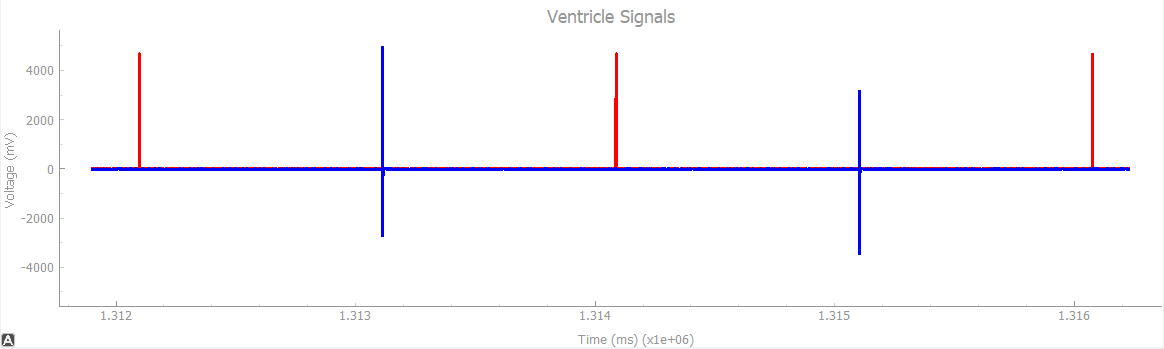
|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| ***VVI Testing outcomes*** | | | | | | |
| **Test Case** | | | | **Expected Result** | **Actual Result** | **Pass/Fail** |
| **Natural Atrium** | **Natural Ventricle** | **Heart Rate (bpm)** | **Pulse width (ms)** |
| OFF | ON | 30 | 1 | Provides artificial pulse when time elapsed since last pulse is greater than 1000ms | Provides artificial pulse when time elapsed since last pulse is greater than 1000ms | Pass |
| OFF | ON | 30 | 10 | Provide a pulse to bridge the gap between spaced out original pulses due to slow bpm | Provide a pulse to bridge the gap between spaced out original pulses due to slow bpm | Pass |
| OFF | ON | 50 | 1 | Send pulse to account for low pulse width | Send pulse to account for low pulse width | Pass |
| OFF | ON | 50 | 10 | No artificial pulses produced | No artificial pulses produced | Pass |

1. Natural Atrium: **OFF** |Natural Ventricle: **ON**, Pulse Width: **1ms** | Heart Rate: **30bpm**

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*

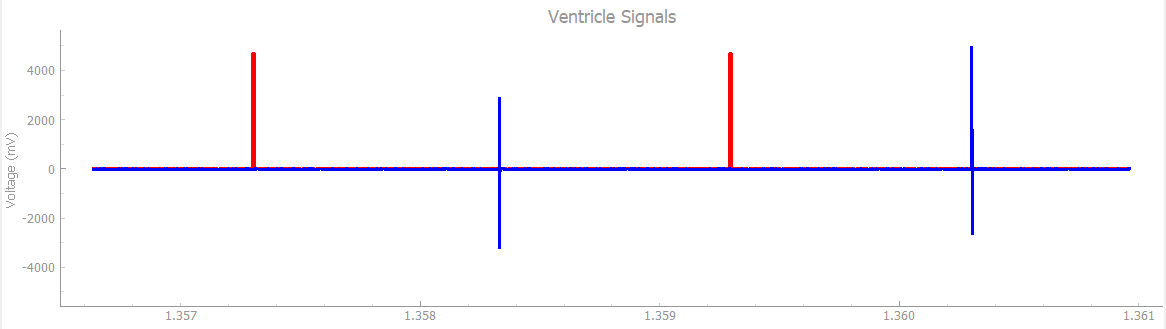


1. Natural Atrium: **OFF** |Natural Ventricle: **ON**, Pulse Width: **10ms** | Heart Rate: **30bpm**

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*

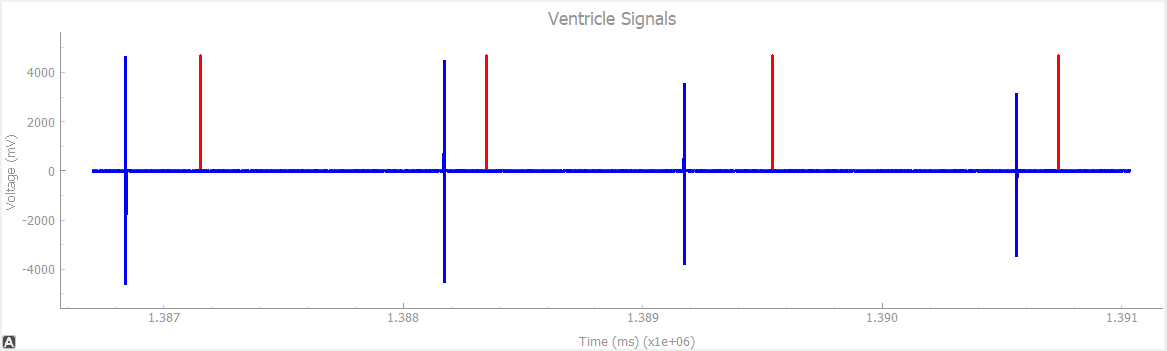


1. Natural Atrium: **OFF** |Natural Ventricle: **ON**, Pulse Width: **1ms** | Heart Rate: **50bpm**

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*



1. Natural Atrium: **OFF** |Natural Ventricle: **ON**, Pulse Width: **10ms** | Heart Rate: **58bpm**

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*

