

DDD Pacemaker Model Checking Report

1. Heart Model

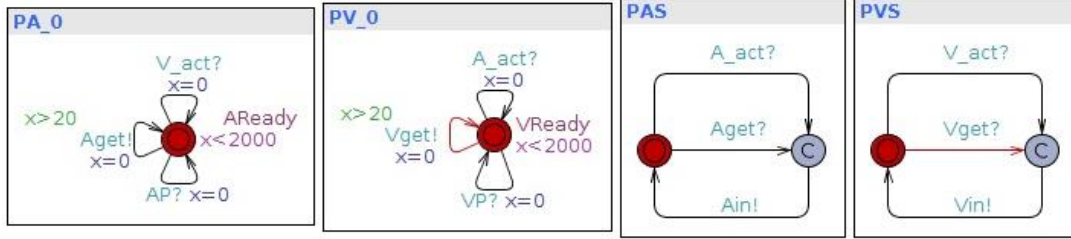


Fig0. Timed-automata Heart Model in UPPAAL

An abstract heart model is implemented so to recover electrical behaviors observable to a pacemaker in a large variety of heart conditions. The implemented heart model is able to generate Ain, Vin, and uses guard expressions to ensure atrial and ventricular rate.

2. Pacemaker Model

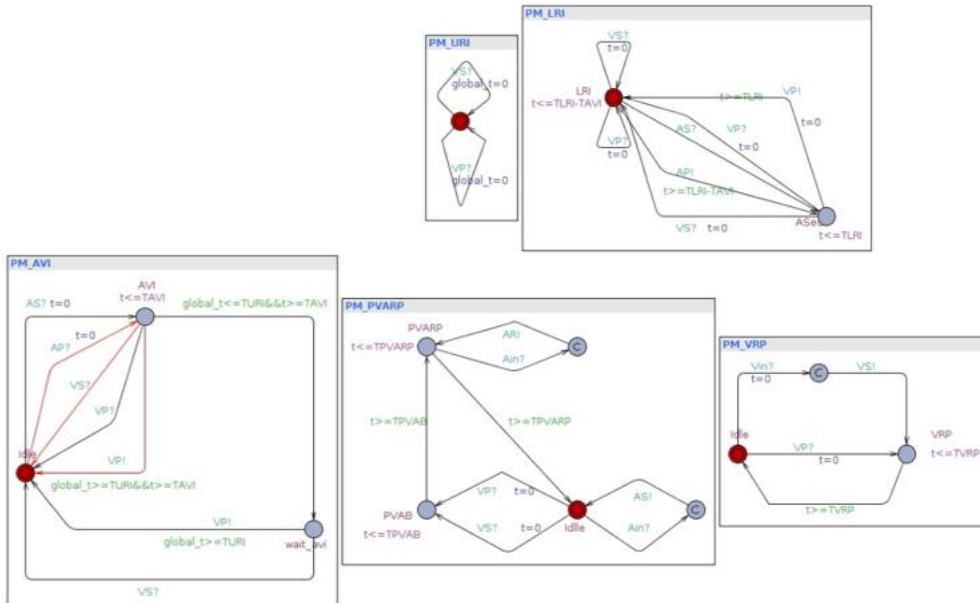


Fig1. Timed-automata Pacemaker Model in UPPAAL

Pacemaker model interact with heart by synchronizing generated atrial pacing and ventricular pacing according to Ain and Vin signals, satisfying the following requirements specified in the query.

2.1 Not deadlock

$A[]$ (not deadlock)

The Pacemaker will always be able to progress instead of stuck in some state

2.2 Lower Rate Limit

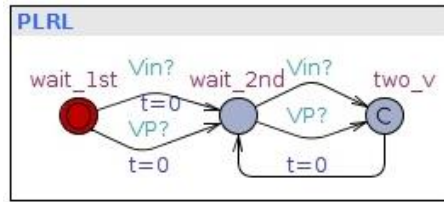


Fig2. LRL part of model checking

A[] (PLRL.two_v imply PLRL.t<=TLRI)

The pacemaker can maintain a minimum ventricular rate, which is, the maximum interval between two consecutive ventricular events is guaranteed to be less or equal to LRI, fulfilling its intended use,

2.3 Upper Rate Limit

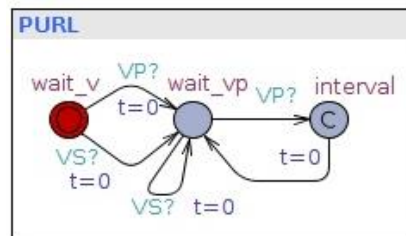


Fig3. URL part of model checking

A[] (PURL.interval imply PURL.t>=TURI)

The pacemaker will not pace to inappropriately increase the heart rate. It makes sure that the minimum interval between a ventricular event and a ventricular pacing is no less than URI.

2.4 Persistent fast ventricular events

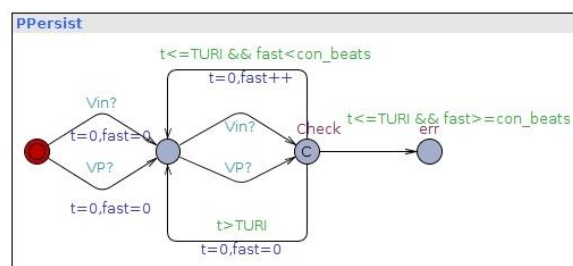


Fig4. Persist part of model checking

A[] (not PPersist.err) (Failed)

With this pacemaker model, the ventricular rate may be faster or equal to URL for more than 30 beats.

2.5 Counter-examples visualization

Atrial Tachycardia Response

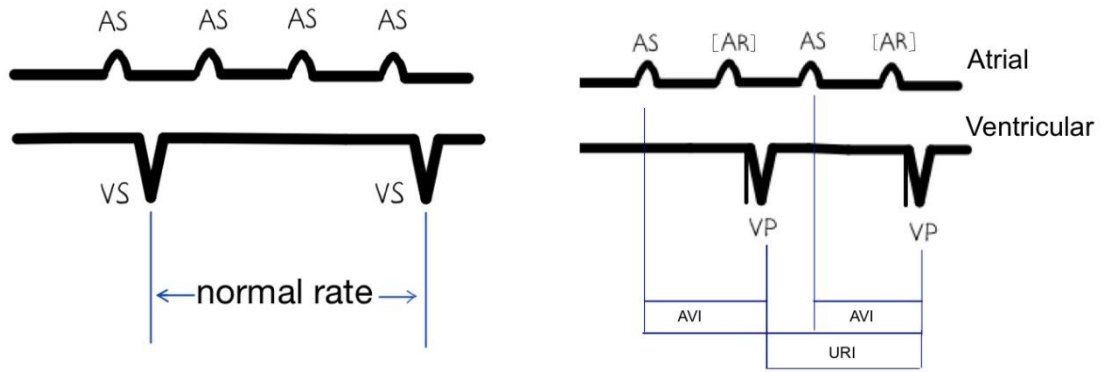


Fig6. ATR without pacemaker(left), ATR with pacemaker(right)

Without pacemaker, AV node blocks part of contraction from passing down to ventricular during an atrial fibrillation.

After adding a pacemaker, the pacemaker generates ventricular pacing continuously and rapidly every URI interval while atrial fibrillation, making ventricular pacing keeps happening with maximum rate, turning supra-ventricular tachycardia to ventricular tachycardia.

Endless-Loop Tachycardia

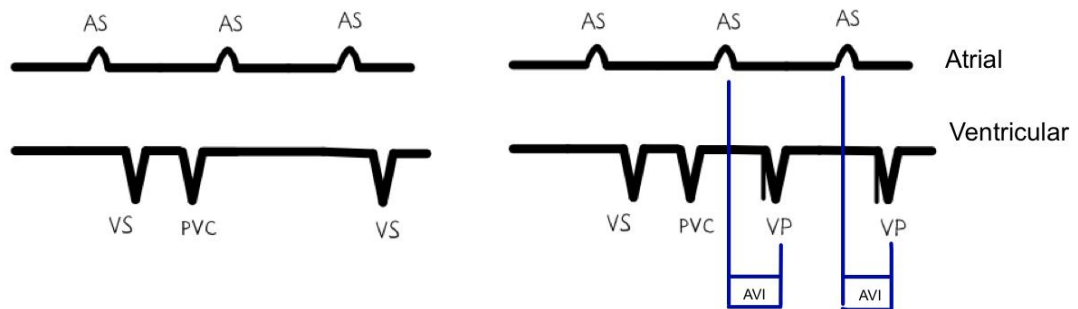


Fig6. PVC without pacemaker(left), PVC with pacemaker(right)

Random heart event(e.g. PVC, premature ventricular contraction) triggers retrograde conduction, causing pacemaker to generate a ventricular pacing after AVI time, than the VP-AS-VP pattern persists, inappropriately increase rate of ventricular events, resulting in endless-loop tachycardia.

2.6 Checking Results

A[] (not deadlock)	●
A[] (PLRL.two_v imply PLRL.t<=TLRI)	●
A[] (PURL.interval imply PURL.t>=TURI)	●
A[] (not PPersist.err)	●

Fig5. Model Checking result of queries in UPPAL