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This form is a summary description of the model entitled "PaceMaker" proposed for the Model Checking Contest @ Petri Nets. Models can be given in several instances parameterized by scaling parameters. Colored nets can be accompanied by one or many equivalent, unfolded P/T nets. Models are given together with property files (possibly, one per model instance) giving a set of properties to be checked on the model.

Description

This model was jointly designed by B. Barbot, M. Kwiatkowska, A. Mereacre and N. Paoletti.

This model includes the key components of the electrical conduction system of the human heart (Fig. 1) and is a P/T net translation of the model in [lian2010]. The model can reproduce antegrade conduction (green arrows in the figure), arising when a stimulus is generated by the sinoatrial (SA) node and is propagated towards the ventricle passing through atrium and the atrio-ventricular (AV) node. The impulse can also start from the ventricle (either intrinsically by component VRG or artificially by the pacemaker) and propagate in the opposite direction (retrograde conduction, red arrows). The transmission of cardiac waves between the atrium and ventricle is mediated by the AV node component (AVJ) and by intermediate conduction nodes (AVJOut, RAConductor and RVConductor). The model can reproduce, among others, ectopic beats (through components SANodeEctopic and VRGEctopic) and the collision of cardiac waves leading to fusion beats. The artificial pacemaker is connected to the atrium and ventricle, and can both sense and stimulate them by delivering electrical impulses.

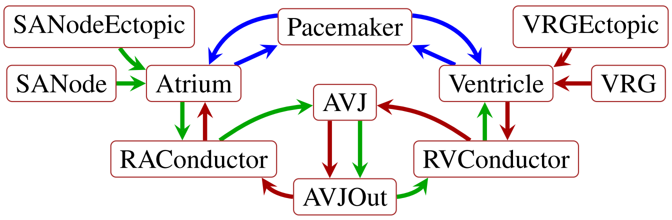
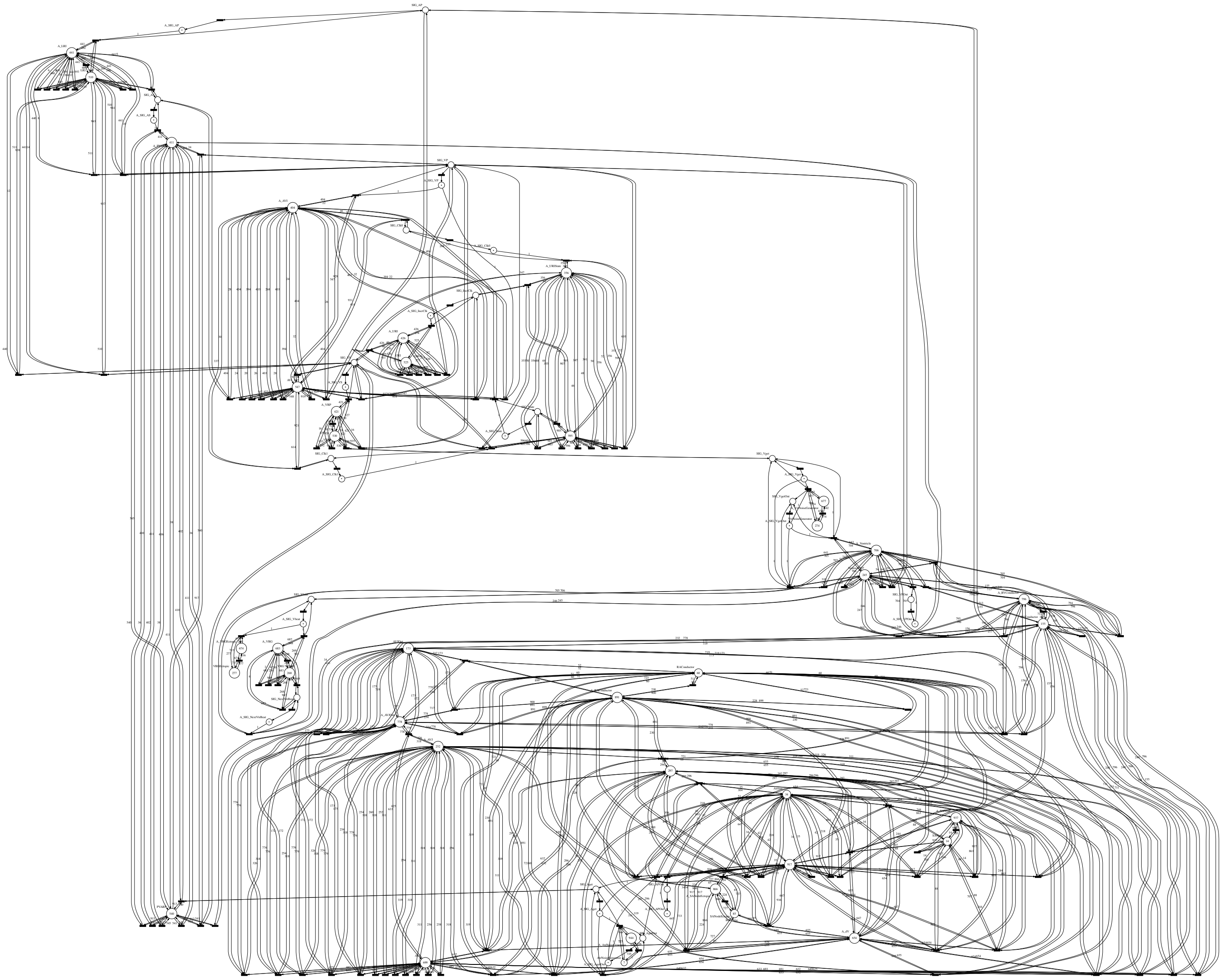


Figure 1: Outline of the heart model

This model is the underlying structure of the timed model described in [BKMP15,BKMP16] which is a formalisation, as a network of timed automatons, of the model presented in [LKMS10].



Graphical representation

References

[BKMP15] B. Barbot, M. Kwiatkowska, A. Mereacre, and N. Paoletti. Estimation and verification of hybrid heart models for personalised medical and wearable devices. In *13th International Conference on Computational Methods in Systems Biology (CMSB 2015)*, volume 9308 of *LNCS*, pages 3–7. Springer, 2015.

[BKMP16] : B. Barbot, M. Kwiatkowska, A. Mereacre, and N. Paoletti. Building Power Consumption Models from Executable Timed I/O Automata Specifications. In 19th International Conference on Hybrid Systems: Computation and Control, HSCC'16, ACM, 2016.

[LKMS10] J. Lian, H. Krätschmer, D. Müssig, and L. Stotts. Open source modeling of heart rhythm and cardiac pacing. *Open Pacing Electrophysiol. Ther. J.*, 3:4, 2010.

Scaling parameter

This model is not parameterized.

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Size of the model

number of places:	70
number of transitions:	164
number of arcs:	954

Structural properties

ordinary — *all arcs have multiplicity one* ✗
simple free choice — *all transitions sharing a common input place have no other input place* ✗ [a]
extended free choice — *all transitions sharing a common input place have the same input places* ✗ [b]
state machine — *every transition has exactly one input place and exactly one output place* ✗ [c]
marked graph — *every place has exactly one input transition and exactly one output transition* ✗ [d]
connected — *there is an undirected path between every two nodes (places or transitions)* ✓ [e]
strongly connected — *there is a directed path between every two nodes (places or transitions)* ✓ [f]
source place(s) — *one or more places have no input transitions* ✗ [g]
sink place(s) — *one or more places have no output transitions* ✗ [h]
source transition(s) — *one or more transitions have no input places* ✗ [i]
sink transitions(s) — *one or more transitions have no output places* ✗ [j]
loop-free — *no transition has an input place that is also an output place* ✗ [k]
conservative — *for each transition, the number of input arcs equals the number of output arcs* ✓ [l]
subconservative — *for each transition, the number of input arcs equals or exceeds the number of output arcs* ✓ [m]
nested units — *places are structured into hierarchically nested sequential units* [n] ✗

Behavioural properties

safe — *in every reachable marking, there is no more than one token on a place* ✗ [o]
dead place(s) — *one or more places have no token in any reachable marking* ?
dead transition(s) — *one or more transitions cannot fire from any reachable marking* ✗
deadlock — *there exists a reachable marking from which no transition can be fired* ✗
reversible — *from every reachable marking, there is a transition path going back to the initial marking* ✓
live — *for every transition t, from every reachable marking, one can reach a marking in which t can fire* ✓

Size of the marking graph

number of reachable markings:	368,026,085,700,403,200
number of transition firings:	?
max. number of tokens per place:	949
max. number of tokens per marking:	18085 [p]

[a] the net is not ordinary.
[b] the net is not ordinary.
[c] the net is not ordinary.
[d] the net is not ordinary.
[e] stated by CÆSAR.BDD version 2.6.
[f] stated by CÆSAR.BDD version 2.6.
[g] stated by CÆSAR.BDD version 2.6.
[h] stated by CÆSAR.BDD version 2.6.
[i] stated by CÆSAR.BDD version 2.6.
[j] stated by CÆSAR.BDD version 2.6.
[k] 148 transitions are not loop free, e.g., transition “D10_q0”.
[l] stated by PNML2NUPN 1.5.1.
[m] stated by PNML2NUPN 1.5.1.
[n] the definition of Nested-Unit Petri Nets (NUPN) is available from `http://mcc.lip6.fr/nupn.php`
[o] in the initial marking, there exist 38 places containing between 7 and 944 tokens.
[p] number of initial tokens, because the net is conservative.

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Other properties

In CTL liveness of the heart is described as:

$$AF(SIG_getOut = 1 => EF(SIG_getOut))$$

The stronger property

$$AF(SIG_getOut = 1 => AF(SIG_getOut))$$

is false due to the many self-loops in the system.

Interesting events in the system are modelled with places with names prefixed by "SIG_", which are 1-safe and encode atomic proposition.