Real-Time Heart Disease Models with Closed-Loop Device Interaction

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Abstract

High fidelity, biophysical computer models of cardiac electrophysiology can help assess conduction mechanisms and plan clinical procedures. However, computational costs mean they are not tools for interacting with cardiovascular implantable electronic devices (CIED) in real-time closed loop. While alternative models have been tested, none successfully encode the electrophysiology dynamics generating complex sensing electrograms (EGMs) for CIEDs.

A robust hybrid-automata modelling approach is adapted to electrophysiology and activation dynamics. This is deployed on conduction networks derived from CT images. They execute on a Simulink® platform and are seamlessly deployed to real-time target machines and combined with interface circuits for hardware-in-the-loop interaction with CIEDs. This is a Paced Automata model of Cardiac Electrophysiology in Real time (PACER).

Early results for probing the PACER model EGM outputs with external pulse pacing inputs in real-time are presented. In future, implementing these ideas in a true closed loop scenario with a programmed pacemaker is envisioned.

1. Introduction

Treating cardiac issues increasingly involves more advanced imaging and devices that give data specific to a patient in order to give precise treatment [1, 2]. Incorporating these different modalities, the field of cardiac computational modelling has expanded to bring together different data sets for a given patient. Computational modelling can help to eliminate some of the costs with testing as well as improve our knowledge base on the actions of disease. However, with the complexity required to model the different functional levels of the heart, modelling the full heart and running at real-time speeds is a computationally intensive task. Typically, the biophysical complexities are abstracted out and key dynamics are maintained at varying strata of the heart [3].

The model, Paced Automata for Cardiac Electrophysiology in Real-time (PACER) abstracts the biophysical precision of cellular modelling whilst maintaining action potential dynamics in order to build electrograms (EGMs) with less computational overhead complexity [4,5]. As a result, patient-specific analogue EGM signals can be generated in real-time with an example 3D heart model composed of 943 nodes and connected by 2820 edges taking 20.8 ± 0.5 s to simulate 30 s of electrophysiology in normal and abnormal rhythms and provides atrial and ventricular EGMs at a guaranteed frequency of 1 kHz.

This work discusses the implementation of PACER network models on a Speedgoat® device, a hardware accelerator that is capable of computing complicated equations quickly and allows the model to run in real time while also interacting with an external device.

2. Methods

Two separate models were considered for testing the capabilities of real-time compilation. The first, is a full 3D heart model and the second, is a simplified 43-node model that encapsulates the main components of the cardiac conduction system. The P3 Speedgoat® device specifications are an 8-core Intel Core 3.6 GHz processor with 128 GB of RAM. A test set up was constructed to output EGMs from the PACER model using a step size of 0.5 ms and probing the model with pacing pulses to the atria and ventricles. A function generator was used to send pulses with widths of 0.24 ms at a frequency of 1 Hz replicating typical pacemaker protocols. The voltage was varied to investigate whether the difference in output ranges between the model and the function generator made a difference.

3. Results

In the instance of the full 3D heart model, the time step of 0.5 ms was too computationally intensive, and even with loosening overload limits the model only ran until 0.7445 s before overloading.

The reduced size, 43-node model, did run successfully on the Speedgoat® unit and all of the subsequent figures refer to pacing this model. Deployment of the compiled model took between 100 s and 170 s. During model runtime, the longest computation time was found at initialisation which ran at between 0.091 ms and 0.098 ms before

gradually speeding up to a task execution time of between 0.035-0.044 ms for every 0.5 ms of cardiac activity. The following plot, Figure 1, shows the ventricular (VEGM in pink) and atrial (AEGM in blue) traces. This colour coding holds for all of the figures.

Figure 1. Oscilloscope trace of the 43-node PACER model with no external influence (pink trace correlates with VEGMs, and blue trace correlates with AEGMs).

It is noticeable that while the AEGM shows a complete trace, the VEGM is clipped during its greatest amplitude.

The following oscilloscope traces (Figures 2-5) were generated while pacing the atrial region with the external function generator. And in them, the green trace represents the atrial pacing (AP) signal received by the Speedgoat while the yellow trace represents the AP that is transmitted to the atrium. Figure 2 shows a pacing pulse received slightly after atrial repolarisation while the ventricles have just finished contracting.

Using the same amplitude, stimulating the atria leads to ventricular depolarisation in Figure 3. In Figure 4 a AP is received during atrial repolarisation and is not transmitted, but when it returns, the signal stimulates the atria. Figure 5 shows an AP event triggering ventricular downstream and another AP event falling into atrial repolarisation and being ignored.

Figures 6 to 8 are instances of pacing the right ventricle of the model, with the green trace referring to the ventricular pacing (VP) signal received by the Speedgoat, and the yellow trace referring to the VP signal transmitted to the model's ventricle.

Figure 6 and 8 are detailing similar instances of timing related ventricle-atrial conduction at different voltages. In the former, the introduced VP triggers atrial contraction which then triggers ventricular contraction after a delay, while in the latter, two ventricular repolarisation signals are instead received. Figure 7 shows nearly exactly the same timing between the AEGM and VEGM signals which suggests that dyssynchrony has been induced.

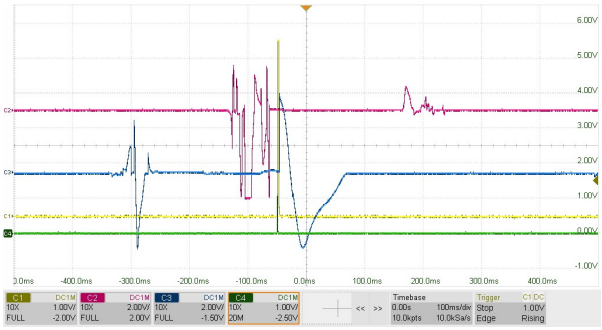

Figure 2. Oscilloscope traces of the 43-node PACER model pacing the right atrium with a voltage amplitude of 1.1 V.

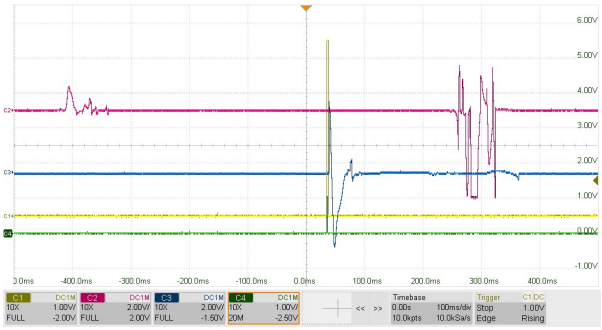

Figure 3. Oscilloscope traces of the 43-node PACER model pacing the right atrium with a voltage amplitude of 1.1 V.

4. Discussion

Promising results with the function generator show that the use of a pacemaker with timing regimes can be tested. The function generator shows that even with a step size of 0.5 ms, the PACER model receives and responds to pacing of 0.24 ms pulse width most of the time. There are instances in both the atrial and ventricular pacing where a signal is received by the Speedgoat but not explicitly processed (Figures 4 and 7). It is suspected that the combinatorial effect of the EGM processing by the model's probes inhibits the transmission. The indiscriminate nature of the voltage range for the model is noted in the magnitude of the baseline EGM traces in Figure 1 being far above the intracardiac EGM ranges for AEGMs and VEGMs which are typically between 1.5 to 6 mV and 5 to 30 mV respectively [6]. The 0.5 ms step size for the current parameterisations and given the failure of the 943-node model to run at real time means that the precise nature of pacemaker timings in the real world are not currently possible.

The other caveats with this are caused by the model digesting the external signal for internal use that turns the

Figure 6. Oscilloscope traces of the 43-node PACER model pacing the right ventricle with a voltage amplitude of 1.1 V.

Figure 7. Oscilloscope trace of the 43-node PACER model pacing the right atrium with a voltage amplitude of 1.9 V.

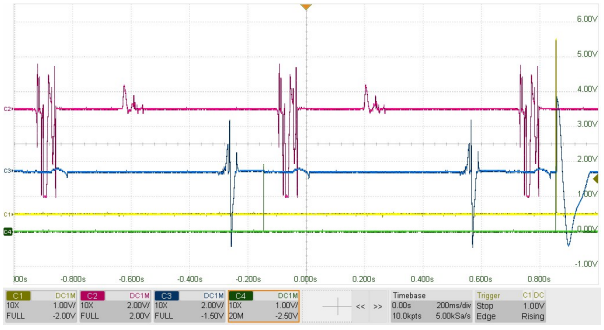

Figure 4. Oscilloscope traces of the 43-node PACER model pacing the right atrium with a voltage amplitude of 1.9 V

Figure 5. Oscilloscope traces of the 43-node PACER model pacing the right atrium with a voltage amplitude of 2.1 V.

scenario into a binary pacing/no pacing scenario. This is seen across all of the plots as no matter the input pacing pulse, the transmitted response is of the same amplitude very time. Crucially the timing at which a pacing event occurs seems to be the most significant factor; as Figures 2, 5 show successful instances of early depolarisation, while figures 4, and 7 show instances of failed event transmission, regardless of signal amplitude or region. Atria to ventricle conduction and ventricle to atria conduction are shown off in Figures 3, 6, and 8 which proves the ability to external disturb the natural heart rhythm of the model with this setup. Implicitly, this also means that controlled restoring of pathological heart rhythms would be possible from an external device and after the voltage ranges are dampened in the EGMs, the model is functionally close to a heart that could be recognised by a CIED.

5. Conclusion

The function generator worked as a sufficient substitute for a pacemaker in eliciting a response from the 43-node PACER network. Timing was triggered between the atria and ventricles in both the anterograde and retrograde directions of the heart's main conduction system. Dampening the amplitude of the model's EGMs should allow a pacemaker to recognise the range as being within human tolerance.

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References

[1] Niederer SA, Lumens J, Trayanova NA. Computational models in cardiology. Nat Rev Cardiol February 2019; 16(2):100–111.

Figure 8. Oscilloscope traces of the 43-node PACER model pacing the right atrium with a voltage amplitude of 2.1 V.

[2] van Osta N, van Loon T, Lumens J. Individual hearts: computational models for improved management of cardiovascular disease 2026;112(11):589–597. ISSN 1355-6037.

[3] Human-heart-model for hardware-in-the-loop testing of pacemakers. Computers in Biology and Medicine 2024; 180:108966. ISSN 0010-4825.

[4] Yip E, Andalam S, Roop PS, Malik A, Trew ML, Ai W, Patel N. Towards the emulation of the cardiac conduction system for pacemaker validation 2018;2(4). ISSN 2378-962X.

[5] Ai W, Patel ND, Roop PS, Malik A, Andalam S, Yip E, Allen N, Trew ML. A parametric computational model of the action potential of pacemaker cells. IEEE Transactions on Biomedical Engineering 2018;65(1):123–130.

[6] 3 - sensing and detection. In Ellenbogen KA, Kay GN, Lau CP, Wilkoff BL (eds.), Clinical Cardiac Pacing, Defibrillation and Resynchronization Therapy (Fourth Edition), fourth edition edition. Philadelpia: W.B. Saunders. ISBN 978-1-4377-1616-0, 2011; 56–126.

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