Modeling Cardiac Pacemakers With Timed Coloured Petri Nets And Related Tools

MODELING CARDIAC PACEMAKERS WITH TIMED COLOURED PETRI NETS AND RELATED TOOLS

BY

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To the memory of my late father (1956-2018)

ABSTRACT

Verification Grand Challenge is one of the Grand Challenges for Computing Research. Verification, which is the strict proof of the correctness of software according to its specifications, results in reliable software and potential cost reductions. In addition, the capabilities of other software engineering techniques, such as requirements analysis and testing, can be complemented and extended by verification. Medical devices are well-known examples of safety-critical systems which require significant advances in verification (among other areas). The failure of safety-critical systems not only damages property or the environment but could also lead to human fatality. Therefore, software verification is one approach to prevent such negative consequences.

The cardiac pacemaker is an electronic device that monitors and controls the heart rhythm via sensing and pacing operations. The pacemaker treats cardiac arrhythmia, defined as abnormal patterns of the heartbeat. The Software Quality Research

Laboratory at McMaster University proposed the pacemaker system specification as a pilot problem for the Verified Software Initiative.

This research utilizes formal methods to model and verify the interdisciplinary requirements of pacemaker systems. It additionally provides customizable data to assess and optimize various algorithms and parameters.

Keywords:

Cardiac Pacemakers · Verification Grand Challenge · Electrocardiogram · Timed Coloured Petri Nets · Biomodelling.

NOTATION AND ABBREVIATIONS

AP	Atrial Pace
ARP	Atrial Refractory Period
AS	Atrial Sense
ATR	Atrial Tachycardia Response
AV	Atrial-to-Ventricular
BOM	Bradycardia Operation Mode
BPM	Beats Per Minute
CCS	Cardiac Conduction System
CPN	Coloured Petri Net
CPS	Cardiac Pacemaker System
DCM	Device Controller-monitor
ECG	Electrocardiogram, external heart signals

EGM	Electrogram, internal heart signals
EP	Electrophysiology, electrophysiologist
FDA	Food and Drug Adminstration
HRL	Hysteresis Rate Limit
LRL	Lower Rate Limit
MSR	Maximum Sensor Rate
PG	Pulse Generator
ppm	Pulses Per Minute
PN	Petri Net
PVARP	Post-Ventricular Atrial Refractory Period
PVC	Premature Ventricular Contraction
SA	Senatorial Node
TCPN	Timed Coloured Petri Net
URL	Upper Rate Limit
VA	Atrioventricular Node
VP	Ventricular Pace
VRP	Ventricular Refractory Period

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1

INTRODUCTION

In this chapter, section 1.1 presents a background for this research. Section 1.2 defines the research aims, while section 1.3 addresses the involved scope of this work. Finally, section 1.4 illustrates the structure of the thesis.

1.1 Background

Verification Grand Challenge is one of the Grand Challenges for Computing Research that has been proposed in [Barbosa et al. [2013]]. Verification is the strict proof of the correctness of software according to its specification, resulting in reliable software and usually cost reductions [Hoare et al. [2009]]. In addition, the capabilities of other software engineering techniques, such as requirements analysis and testing, can be complemented and extended by verification.

Medical devices are well-known examples of safety-critical systems [Knight [2002]], which required significant advances in verification (among other areas). The failure of safety-critical systems not only damages property or the environment but also could lead to the death of people. Between 2006 and 2011, the US Food and Drug Administration (FDA) reported 2,294 fault cases and 1,154,451 side effects cases due to the faults of medical devices. Among those cases, there were 92.600 cases of patient injury and 4.590 cases of patient death. Almost 23 percent of these failures are related to software applications of medical devices [Alemzadeh et al. [2013]]. Therefore, software verification is one approach to prevent such faults.

The cardiac pacemaker (pacemaker thereafter) is an electronic device that monitors and controls the heart rhythm via sensing and pacing operations. The pacemaker treats abnormal patterns of the heartbeat, which is called cardiac arrhythmia. The Software Quality Research Laboratory at McMaster University proposed the pacemaker system specification [Boston Scientific [2007]] as a pilot problem for the Verified Software Initiative [Woodcock [2006]].

1.2 Research Aims

This thesis aims to verify the pacemaker system specification that represents its functions and operating properties. This can be translated into three objectives. Formal methods based on Timed Coloured Petri Nets (TCPNs) to model and verify the interdisciplinary requirements of pacemaker systems. Formal methods to precisely present and produce realistic synthetic events of the cardiac electrical activities to validate the pacemaker's various parameters. Finally, formulating a system to build proper and related datasets from the above models' processed data for further analysis, optimization and employment.

1.3 Scope

The work of this thesis involves studying the applicability of Timed Coloured Petri Nets (TCPNs) for the modelling and analysis of safety-critical systems. Timed Coloured Petri Nets were utilized to verify and validate the pacemaker specification and parameters. In addition, it assessed the feasibility of applying an evolutionary approach to develop a model for an artificial cardiac pacemaker.

1.4 Structure of the Thesis

The structure of this research is as follows:

- Chapter 2 provides backgrounds for the pacemaker system and environment. It also discusses related work and system requirements.

- Chapter 3 introduces the Timed Coloured Petri Nets (TCPN), which is the used modelling language of theproposed models.
- Chapter 4 presents in detail the TCPN-based modelling of the Cardiac Conduction System (CCS).
- Chapter 5 extends the model from chapter 4 to include the TCPN-based modelling of the Cardiac Pacemaker System (CPS).
- Chapter 6 concludes with the contributions of the thesis, related publications, and future work.