

From Verified Models to Verified Code for Safe Medical Devices

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Thesis Problem

Closed-loop medical devices like implantable pacemakers and implantable cardioverter defibrillators (ICD) diagnose conditions of the patient and autonomously deliver corresponding therapies. The fundamental challenge for developing safe closed-loop medical devices are: 1) how to make correct diagnosis with **limited observability** on the patients' physiology? 2) how to ensure the closed-loop interactions between **complex physiology** and device therapies are always safe? 3) how to develop devices that are general enough to safely operate on large groups of patients with **large variability** in their physiology? In order to address these challenges, the safety and efficacy of closed-loop medical devices have to be evaluated within their physiological contexts, which is currently performed as clinical trials on real patients. However, clinical trials pose significant risks to the patients involved, and safety issues found at this stage are costly to fix. There is urgent need to be able to evaluate device safety earlier during the development process.

Thesis Statement

In this thesis, I proposed model-based approaches to evaluate the safety and efficacy of closed-loop medical devices during their development process, with implantable cardiac devices as case study. I focused on addressing the following questions:

1. What can be the substitutes for real patients in closed-loop evaluations of implantable cardiac devices?

A heart model structure has been developed to model the timing of generation and conduction of electrical events in the heart. The model structure can be configured to represent a large variety of heart conditions. The model structure is available in both software and hardware, and is capable of generating realistic physiological signals to the devices and respond to device outputs.

2. How to ensure the design of the device is safe early in the design process?

Abstract model of the device design can be evaluated in closed-loop with models of patient physiology using model checking. The variability of the patient is captured using non-determinism and the heart models are abstracted to capture the electrical behaviors observable to the devices. An abstraction tree structure has been developed to balance the coverage and expressiveness of the heart models for different safety properties. The result of closed-loop model checking provides safety and efficacy guarantee to the device design, which can contribute to the risk analysis of the device.

3. How to ensure the properties verified in device model still hold in device implementation?

The device model verified in model checker UPPAAL can be automatically translated into Stateflow model through a rigorous model translation tool we developed. The Stateflow model of the device can then be generated into C code using Simulink Coder. This toolchain enables developing the device function with a verifiable model and maintain all verified properties in the final implementation.

4. Can model-based approaches help before the device goes for clinical trials?

A clinical trial is only useful if its result shows statistical significance. A failed trial is a huge cost in time and money, and poses significant risks on the patients involved. Therefore clinical trials need to be planned carefully, with correct estimation of the size of the patient population. In this thesis, I proposed *model-based clinical trial*, in which I use the heart model structure to construct a virtual patient population with different heart conditions. The population, which contains more than 10,000 heart models with different heart conditions, captures the variability of patients' physiological conditions. The device can then be evaluated on the virtual population, and different types of analysis can be performed which can provide useful insights for planning a clinical trial.

The aforementioned model-based approaches form a model-based framework for developing cyber-physical systems, which bridges the gap between the cyber domain and the physical domain.

1 Motivation

Medical devices play an essential role in the care of patients around the world, and can have a life-saving effect. To cite one example, in the US, \sim 800,000 people have an implanted defibrillator (a heart rhythm management device), with 10,000 added monthly. Clinical trials have presented evidence that patients implanted with defibrillators have a mortality rate reduced by up to 31%. Examples include everything from adhesive bandages to drug infusion pumps, surgical robots, deep brain stimulation systems and devices still undergoing

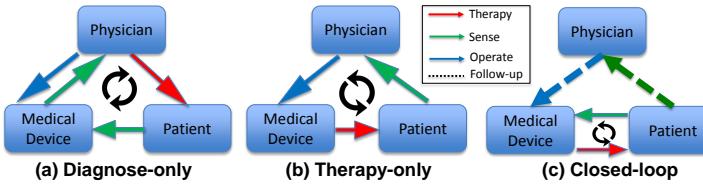


Figure 1: Open-loop and closed-loop medical devices. The open-loop devices has medical professionals in the loop while the closed-loop medical devices interact with patient physiology directly.

basic research like the artificial pancreas. These are safety-critical technologies combining hardware and software, each of which must be rigorously validated to be efficacious and safe.

One way to categorize medical devices is according to the way the device interacts with patient's physiology. One category is *open-loop medical device* which has only therapeutic or diagnostic capability, i.e. X-ray machine and infusion pumps. Open-loop medical devices are normally operated by professional medical care providers, which provides reliable safety guarantees (Fig. 1). On the other hand, there is an emerging category referred to as *closed-loop medical devices*, which has both therapeutic and diagnostic capability. An example of closed-loop medical devices is implantable pacemaker which diagnoses patient condition through sensed electrogram signals and delivers electrical pacing to maintain appropriate heart rhythm (Fig. 2). Closed-loop medical devices interact with human physiology in closed-loop, and often times without human intervention. Therefore device failures like inappropriate therapies may not receive timely intervention, which can result in serious injuries or death of the patient. As the result, closed-loop medical devices are categorized by the regulation agencies as the highest risk devices.

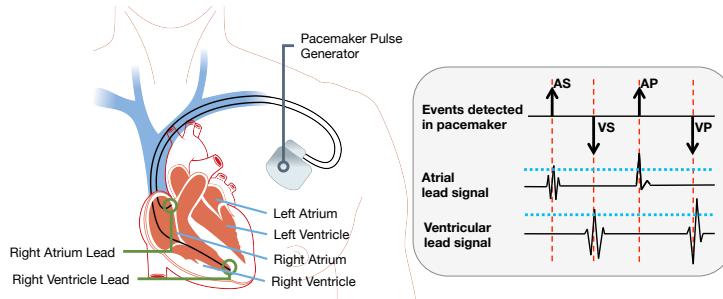


Figure 2: Pacemaker operating in a closed-loop with the heart. The leads sense cardiac electrophysiological activity from inside the heart tissue (AS/VS = Atrial/Ventricular Sense event) and actuate the heart (AP/VP = Atrial/Ventricular Pacing event to maintain a desired heart rate).

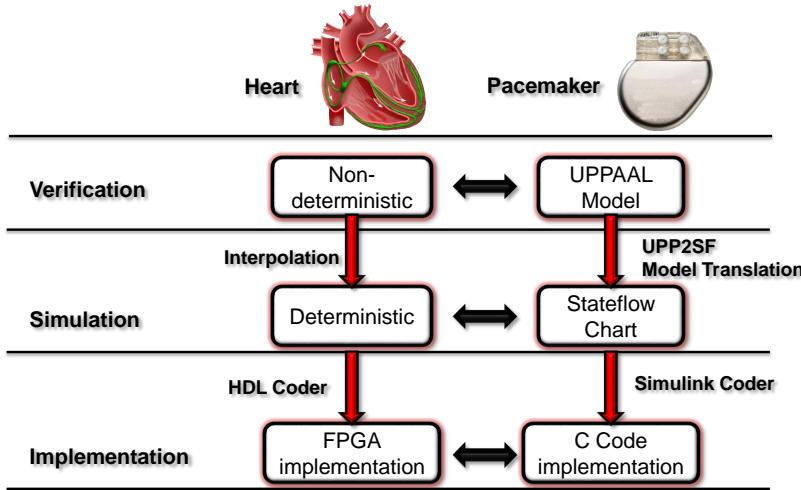


Figure 3: Model-based design framework for implantable cardiac devices. Models of the heart are developed and the variations of the heart models can be used for closed-loop evaluation of the devices during their development process. A device can be first developed as an abstract model. The safety and efficacy of the device design can be evaluated using closed-loop model checking. The verified device model can then be automatically translated into code implementation while preserving all properties.

2 Research Completed

In this thesis, I propose a model-based design framework for closed-loop validation of medical devices, and use implantable cardiac devices as case study. Fig. 3 demonstrates our model-based design framework for implantable pacemaker software. The thesis can be broken down into 4 themes: Theme 1 discusses the physiological models that are necessary for closed-loop evaluation of medical devices, and how to use those models to represent complex physiology with large variability. Theme 2 discusses the use of model-checking techniques to evaluate the safety and efficacy of device design, which can contribute to risk analysis of the device. Theme 3 discusses the rigorous translation from verified device model to device implementation which maintains the verified properties. Theme 4 discusses the use of physiological models to generate a virtual patient population and the device can go through model-based clinical trials which can provide useful insights for planning a clinical trial on real patient.

2.1 Theme 1: Physiological Modeling for Closed-loop Device Validation

Validation of a device evaluates whether the device has fulfilled its intended use. For instance, an implantable pacemaker is supposed to increase the heart rate above 60bpm. Therefore in order to enable closed-loop validation of implantable cardiac device throughout

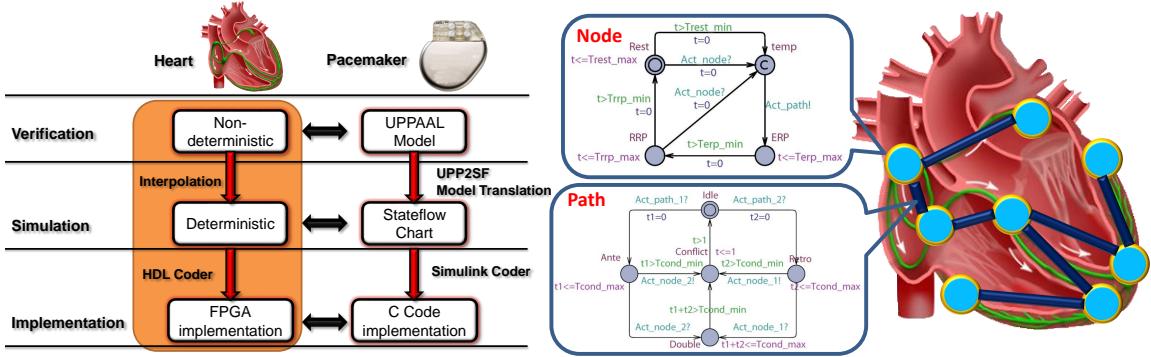


Figure 4: Heart model structure which models generation and conduction of the electrical activities of the heart with a network of timed-automata. The node automata models the generation and blocking of electrical signals and the path automata models the conduction delays between nodes. Highlighted region shows the topic of the theme.

the development process, physiological models of the heart are needed which can interact with the device model in closed-loop.

Challenge: Develop physiological models with respect to the limited observability of the device, while still being able to capture the complexity and large variability of patient physiology.

Contribution: A heart model structure based on clinical electrophysiology, which is also the foundation for implantable cardiac devices. The heart models are capable of interacting with implantable cardiac devices in a closed-loop manner, and are available in different complexity with multiple formalisms for different applications throughout the design process.

2.1.1 Electrophysiology Model of the Heart

The coordinated contractions of heart muscles are governed by electrical activities. Anomalies in the timing and patterns of the electrical generation and conduction are referred to as *arrhythmia*, which are the disease implantable cardiac devices are designed to treat. I used *node automata* to model the timing for electrical signal generation and blocking in heart tissue. Conduction delays between node automata are modeled using *path automata* (Fig. 4). By configuring the node and path automata with different parameters using different topology, the heart model structure can be used to model the electrical behaviors of a large varieties of heart conditions. The heart models can also generate realistic electrogram signals that can be used as inputs to implantable cardiac devices.

2.1.2 Model Variations for Different Applications

Performing closed-loop validation during different stages of the development process pose different requirements to the physiological models.

During closed-loop simulation or hardware testing, the heart models should be able to capture the complex dynamics of *specific hearts* to provide repeatable deterministic executions. Therefore the heart models used for closed-loop simulation are deterministic, and include calculations for parameter changes during state transitions.

During closed-loop model checking, the heart models should be abstract enough to cover the observable behaviors of a large group of patients to account for the large variety of physiological conditions, while at the same time expressive enough to distinguish the heart behaviors specified in the property with the rest. There is no single heart model that can satisfy both requirements, therefore a rigorous framework to balance the abstraction and refinement of the heart models is needed to select the most appropriate heart model for the physiological properties.

2.1.3 Heart-on-a-Chip Platform

In order to interact with implementations of implantable cardiac devices, the heart model structure is also available on hardware. In this thesis, I developed the Heart On a Chip platform (Fig. 5). The heart model is implemented on a FPGA board, which interacts with the devices in real-time via an analog interface. The platform enables us to do closed-loop testing on commercially available devices, which is an important requirement if we would like to do model-based clinical trials before an actual clinical trials.

2.1.4 Heart Model Validation

The heart model structure is based on the first-principle of clinical electrophysiology and parameters of the heart model can be identified from patient data. The heart model structure has been validated by demonstrating the capability to model the mechanisms of different heart conditions including reentry tachycardia, heart blocks, etc.

2.1.5 Publications Related to Physiological Modeling

- **Z. Jiang**, M. Pajic, A. Connolly, S. Dixit, and R. Mangharam. Real-time heart model for implantable cardiac device validation and verification. *In 22nd Euromicro Conference on Real-Time Systems (ECRTS)*, 2010, pages 239 –248, July 2010.
- **Z. Jiang**, M. Pajic, and R. Mangharam. Cyber-Physical Modeling of Implantable Cardiac Medical Devices. *Proceedings of the IEEE*, 100(1):122 –137, Jan. 2012a.
- **Z. Jiang**, M. Pajic, R. Alur, and R. Mangharam. Closed-loop verification of medical devices with model abstraction and refinement. *International Journal on Software*

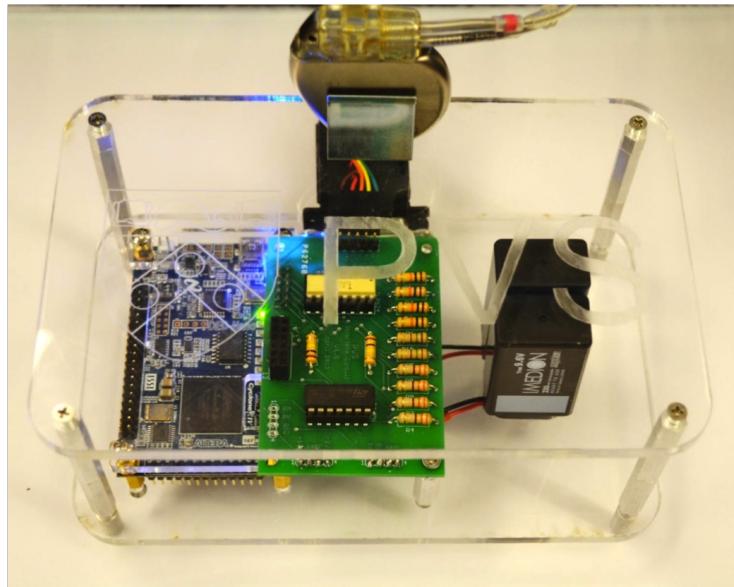


Figure 5: Heart On a Chip platform. A heart on FPGA can interact with a commercial device via an analog interface.

Tools for Technology Transfer, 16(2):191–213, 2014.

- **Z. Jiang** and R. Mangharam. Modeling Cardiac Pacemaker Malfunctions with the Virtual Heart Model. In *Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, 2011 , pages 263 –266, Sept 2011.
- **Z. Jiang**, M. Pajic, and R. Mangharam. Model-based Closed-loop Testing of Implantable Pacemakers. In *ACM/IEEE Second International Conference on Cyber-Physical Systems (ICCP’11)*, 2011.

2.2 Theme 2: Using Closed-loop Model checking for Medical Devices Risk Analysis

Model checking has been widely used in semi-conductor industry which can check the whole state space of a model for property violations. However, model checking has not been applied in the medical device industry due to the lack of appropriate physiological models. Risk analysis is an activity mandated by the regulator to provide confidence to the safety of the device, which is currently performed manually and can miss potentially risks. In this thesis, I demonstrate the use of closed-loop model checking for risk analysis of implantable cardiac devices, and find potential safety violations which are extremely difficult to find via other techniques like testing.

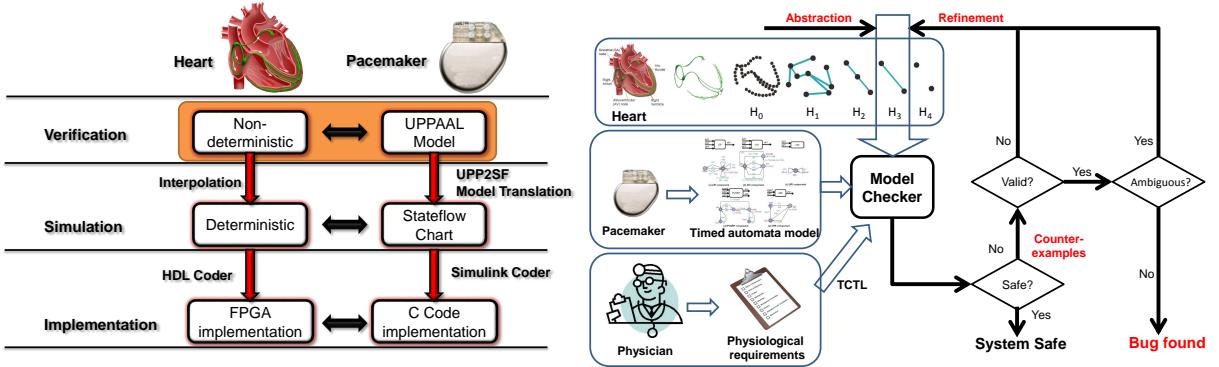


Figure 6: Closed-loop model checking for implantable cardiac devices. Risks of the devices can be specified as physiological properties, and the closed-loop model including a model of the device and heart models with different abstraction level are checked in model checker UPPAAL. Highlighted region shows the topic of the theme.

Challenge: Abstraction of physiological models may introduce false-positives and/or false-negatives. For different physiological properties, the physiological model(s) should capture the large variability of physiology constrained by the property, while maintaining the capability to distinguish complex physiological behaviors.

Contribution: In this thesis I use non-determinism in heart models to cover variabilities of electrical behaviors in a large number of heart conditions. A rigorous abstraction and refinement framework has been developed to choose the most appropriate heart model for a physiological property, and provide physiological explanations to counter-examples returned by the model checker. Risk analysis was performed on a dual chamber implantable pacemaker, which includes risks that can endanger the safety of the patients. By specifying these risks as physiological properties, I used model checking to identify potential risks of the abstract pacemaker model. This research demonstrates the potential for application of model checking in the medical device industry.

2.2.1 Risk Analysis for Implantable Pacemaker

In this thesis, I focused on two most intuitive risks that an implantable pacemaker can pose on patients: 1) The pacemaker fails to increase the ventricular rate no lower than 60bpm, and 2) The ventricular rate is increased inappropriately by the pacemaker. Fault Tree Analysis (FTA) has been performed on the two risks to identify known and unknown causes for the two risks. As new functionality introduced into the device, new potential risks are introduced into the fault tree, which require further analysis. Fig. 7 demonstrates the FTA for one of the risks for pacemaker.

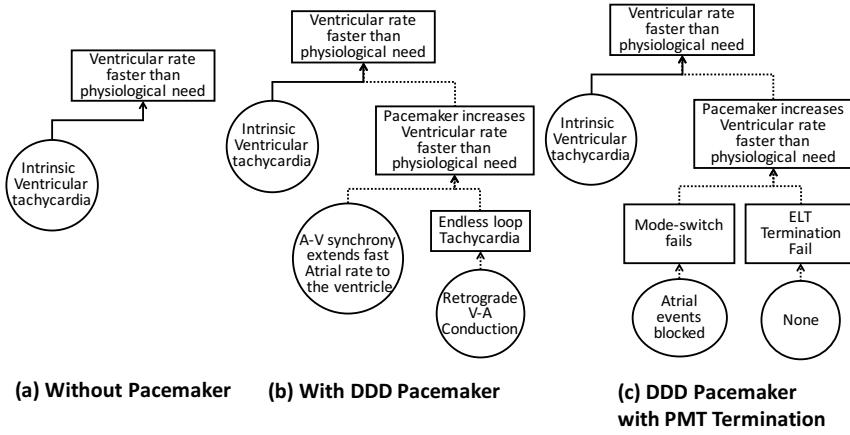


Figure 7: Fault Tree Analysis for the heart. As more functionality is introduced to the device, there are more potential risks.

2.2.2 Closed-loop Model Checking for Risk Analysis of Implantable Pacemaker

All identified causes for the two risks have been specified as Computational Tree Logic (CTL) properties. The closed-loop model which consists of the device model and a physiological model are then verified in model checker UPPAAL. UPPAAL returns evidence of these risks as execution traces, if any. In this thesis, we were able to identify evidence for risks in our pacemaker model, which are almost impossible to find with traditional testing methods. For the additional algorithms designed to terminate Pacemaker Mediated Tachycardia, which is one of the risks, we evaluated their performance in terms of whether the risks have been reasonably *mitigated*. All of the analysis above can be used as evidence for the safety of the device model.

2.2.3 Heart Model Abstraction and Refinement

The major challenge for closed-loop model checking is to develop appropriate physiological models. The models should be general enough to cover physiological behaviors from different patient conditions, while at the same time expressive enough to maintain physiological meanings of an execution trace. There is no single model that can satisfy both requirements for different properties. Using models that are too abstract introduces false-negatives, i.e. physiological-impossible behaviors introduced into the model during abstraction. Moreover, with multiple physiological models, their relationships in terms of coverage is difficult to know, which reduces the rigorousness of the results. It is therefore important to have a

rigorous hierarchy of physiological models with different abstraction levels and a procedure to choose the appropriate model for a property.

In this thesis, we adopted the Counter-Example-Guided Abstraction and Refinement framework to balance the coverage and expressiveness of the heart models (Fig. 6). Each property is checked with the heart model with the most behavior coverage. If an evidence is returned by the model checker, it is manually analyzed for its physiological validity. If the evidence is valid, it is then checked for ambiguity due to the over-abstraction of the model. If the evidence is both valid and unambiguous, the execution is a true evidence for the risk property.

2.2.4 Abstraction Tree for Physiological Model Abstraction and Refinement (in progress)

The method above requires enormous amount of domain knowledge and is time consuming. Therefore we are proposing an automated and rigorous framework for physiological modeling during closed-loop model checking.

First, a set of initial heart models are created by the physicians to cover behaviors of possible heart conditions. The initial set is by no mean exhaustive but provides a solid foundation for model abstraction. Then by applying physiological abstraction rules, the heart models and their behaviors are merged into more abstract models. The abstraction rules introduce new behaviors into the more abstract model which are mostly physiological relevant. By applying physiological abstraction rules in certain order we obtain a tree-like structure for heart model abstractions, which we refer to as the *Abstraction Tree*. During model checking, the most abstract model which covers all possible behaviors of the heart is first used to interact with the device. If a counter-example is found, it is then analyzed in more refined heart models following the abstraction tree for both validity check and de-ambiguity. In the end, the counter-example is either valid in one or more concrete heart models, which provides physiological contexts to the counter-example; or only valid in an intermediate abstraction level, which will be checked by the physician for validity.

The abstraction tree effectively bridges the gap between the physiological domain and the computer science domain, which encourages the application of model checking in medical device development.

2.2.5 Publications Related to Closed-loop Model Checking

- **Z. Jiang**, M. Pajic, S. Moarref, R. Alur, and R. Mangharam. Modeling and Verification of a Dual Chamber Implantable Pacemaker. *Tools and Algorithms for the Construction and Analysis of Systems*, 7214:188–203, 2012b.
- **Z. Jiang**, M. Pajic, R. Alur, and R. Mangharam. Closed-loop verification of medical devices with model abstraction and refinement. *International Journal on Software Tools for Technology Transfer*, 16(2):191–213, 2014.

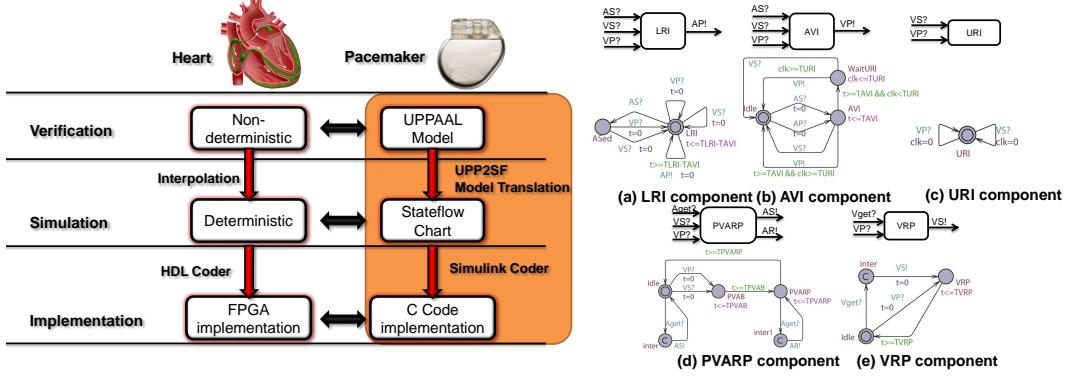


Figure 8: Device model validated during closed-loop model checking can be rigorously translated into C code implementation with model translation and code generation. Highlighted region shows the topic of the theme.

2.3 Theme 3: Verified Model to Verified Code

It is important to maintain *traceability* between models of the devices and device implementations, i.e. requirements validated in the device model should also hold in device implementation.

Challenge: Model translation from abstract formalism in UPPAAL to more expressive formalism in Stateflow.

Contribution: In this thesis I implemented models for implantable cardiac devices by reverse-engineering from algorithm descriptions in publicly available literature. A model translation tool chain has been developed to generate device implementations automatically and rigorously from verified models.

2.3.1 UPPAAL Model of a Dual Chamber Pacemaker

A dual chamber pacemaker senses local electrical events from the right atrium and right ventricle, respectively. The software diagnoses the heart condition by comparing the timing relationship among events. Electrical pacing will be delivered to restore normal heart rhythm if the heart rate is low. Therefore it is intuitive to model the pacemaker functionality as timed-automata. In this thesis, I modeled a dual chamber pacemaker as timed-automata in model checker UPPAAL, using specifications from publicly-available literature (Fig. 8). The model includes the basic 5 timing cycles of a dual chamber pacemaker. I also implemented two additional algorithms that were designed to eliminate *Pacemaker Mediated Tachycardia (PMT)*, during which the pacemaker inappropriately increase the heart rate. Through the experiment I validated the performance of the PMT algorithms, and also evaluated whether implementing additional functionality can violate properties satisfied by the original model.

2.3.2 UPP2SF Model Translation

Due to the limited semantics of the model checking tool, the device model in the model checker is generally an abstraction of the actual device functions. The biggest challenge for model implementation tool chain is how to deal with the additional behaviors in the actual implementation, and how they affect the property preservation. After the device model has mitigated all the risks, it is essential for the device implementation to preserve those properties. In our framework, we developed a model translation tool which rigorously translates device model in UPPAAL model checker to Stateflow chart. The Stateflow chart can then be compiled into C code implementation using Simulink Coder, which completes a tool chain from validated model to validated code.

2.3.3 Publications Related to Device Modeling and Model Translation

- **Z. Jiang**, M. Pajic, S. Moarref, R. Alur, and R. Mangharam. Modeling and Verification of a Dual Chamber Implantable Pacemaker. *Tools and Algorithms for the Construction and Analysis of Systems*, 7214:188–203, 2012b.
- M. Pajic, **Z. Jiang**, I. Lee, O. Sokolsky, and R. Mangharam. From Verification to Implementation: A Model Translation Tool and a Pacemaker Case Study. *In Proceedings of the 2012 IEEE 18th Real Time and Embedded Technology and Applications Symposium, RTAS '12*, pages 173–184, 2012.
- M. Pajic, **Z. Jiang**, I. Lee, O. Sokolsky, and R. Mangharam. Safety-critical medical device development using the upp2sf model translation tool. *ACM Trans. Embed. Comput. Syst.*, 13(4s):127:1–127:26, 2014.

2.4 Theme 4: Model-based Clinical Trials for Medical Devices (in progress)

A clinical trial is only useful if its result shows statistical significance. A failed trial is a huge cost in time and money, and poses significant risks on the patients involved. Therefore clinical trials need to be planned carefully, with correct estimation of the size of the patient population. In this thesis, I proposed *model-based clinical trial (MBCT)*, in which a virtual patient population consists of physiological models are used to represent real patient population. The results of MBCT can provide useful insights for planning the actual clinical trial.

Challenge: How the virtual population comparable to a real population in terms of physiological validity and variability? How much can we claim for results of MBCT?

Contribution: In this thesis I constructed a virtual population which consists of over 10,000 different heart models for 19 different heart arrhythmia. The population can be used to perform model-based analysis which cannot be performed during a real clinical trial, which can provide useful insights for planning the clinical trial.

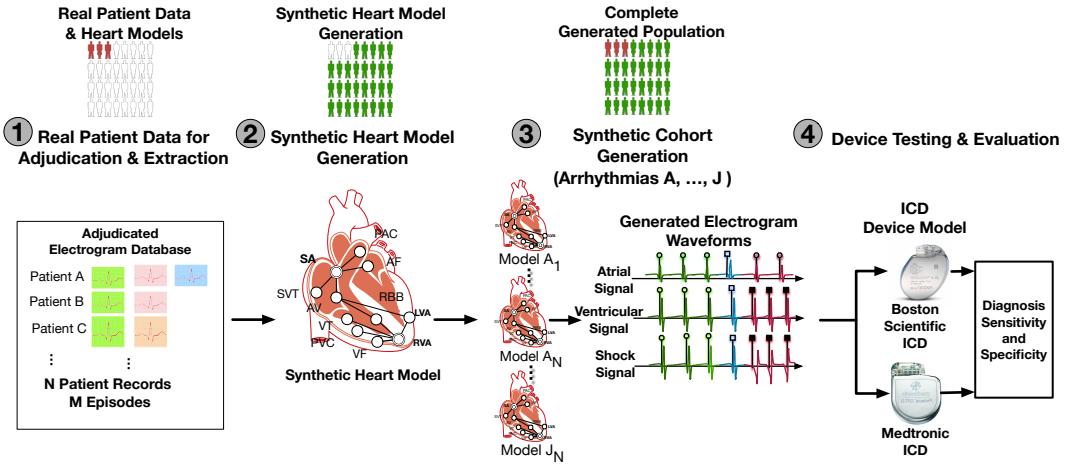


Figure 9: Model-based Clinical Trials for Implantable Cardiac Devices

2.4.1 SVT/VT Discrimination Algorithm of ICDs

Ventricular tachycardia (VT) is a fatal heart condition that can lead to the death of patient in a short period of time. ICDs are designed to treat VTs with high-voltage electrical shocks. The ICDs should always correctly identify ongoing VTs with electrogram signals and deliver shocks to terminate VTs. However, shocks during Supra-Ventricular Tachycardia (SVT) are *inappropriate* and can cause severe discomfort for the patient. ICDs utilize the timing and morphologies of the electrogram singals to distinguish SVT vs. VT, which is difficult given the limited observability of the ICDs.

In this thesis, I implemented SVT/VT discrimination algorithms from two device manufacturers and compared their rate of inappropriate shocks on a virtual patient population consists of 10,000 heart models.

2.4.2 Virtual Population Generation

The virtual population consists of electrophysiology models of the heart which can be parameterized to represent patients with different heart conditions. To generate realistic electrogram signals, real electrogram signals from an electrogram database are adjudicated by a physicians to create a set of electrogram morphologies from different activation sources (① in Fig. 9). The timing of the electrogram activations is ensured by the timing model of the heart (② in Fig. 9). Heart model instances can be created with their parameters within timing constraints for different heart conditions (③ in Fig. 9). Electrogram signals are then generated by combining the timing and morphology components and feed into the two SVT/VT discrimination algorithms (④ in Fig. 9). By generating 600 heart instances for each of the 19 conditions we have a population large enough to ensure statistical significance

for most of the analysis.

2.4.3 Model-based Clinical Trials on SVT/VT Discrimination Algorithms

An actual clinical trial was conducted on the same two SVT/VT discrimination algorithms. The result of our MBCT shows comparable results to the actual trial, which is a validation of our virtual population. We also used the flexibility of the MBCT to perform more analysis which cannot be performed during a real trial (i.e. evaluate devices with different parameter settings on the same patient).

An MBCT is *not* a replacement for a clinical trial: rather, it will allow us to run very large-scale targeted simulated trials to better inform our conduct of an actual clinical trial. This provides valuable insight into which patients should be enrolled in the trial (and in whom the device is most efficacious). Another application would be to get tighter estimates of statistical quantities like effect size needed before the conduct of the trial.

2.4.4 Publications Related To Model-based Clinical Trials

- H. Abbas, **Z. Jiang**, K. Jang, Rahul Mangharam, Model-based Clinical Trials for Medical Devices. International Conference on Cyber-Physical Systems, 2016 (Submitted).

2.5 Publications

2.5.1 Conference Publications

- **Z. Jiang**, M. Pajic, A. Connolly, S. Dixit, and R. Mangharam. Real-time heart model for implantable cardiac device validation and verification. In *22nd Euromicro Conference on Real-Time Systems (ECRTS)*, 2010, pages 239 –248, July 2010.
- **Z. Jiang** and R. Mangharam. Modeling Cardiac Pacemaker Malfunctions with the Virtual Heart Model. In Engineering in Medicine and Biology Society,EMBC, 2011 Annual International Conference of the IEEE, pages 263 –266, Sept 2011.
- **Z. Jiang**, M. Pajic, and R. Mangharam. Model-based Closed-loop Testing of Implantable Pacemakers. In ACM/IEEE Second International Conference on Cyber-Physical Systems (ICCP’11), 2011.
- **Z. Jiang**, M. Pajic, S. Moarref, R. Alur, and R. Mangharam. Modeling and Verification of a Dual Chamber Implantable Pacemaker. Tools and Algorithms for the Construction and Analysis of Systems, 7214:188–203, 2012b.
- M. Pajic, **Z. Jiang**, I. Lee, O. Sokolsky, and R. Mangharam. From Verification to Implementation: A Model Translation Tool and a Pacemaker Case Study. In Proceed-

ings of the 2012 IEEE 18th Real Time and Embedded Technology and Applications Symposium, RTAS '12, pages 173–184, 2012.

2.5.2 Journal Publications

- **Z. Jiang**, M. Pajic, and R. Mangharam. Cyber-Physical Modeling of Implantable Cardiac Medical Devices. *Proceedings of the IEEE*, 100(1):122 –137, Jan. 2012a.
- **Z. Jiang**, M. Pajic, R. Alur, and R. Mangharam. Closed-loop verification of medical devices with model abstraction and refinement. *International Journal on Software Tools for Technology Transfer*, 16(2):191–213, 2014.
- M. Pajic, **Z. Jiang**, I. Lee, O. Sokolsky, and R. Mangharam. Safety-critical medical device development using the upp2sf model translation tool. *ACM Trans. Embed. Comput. Syst.*, 13(4s):127:1–127:26, 2014.

2.5.3 Book Chapters

- **Z. Jiang** and R. Mangharam. High-Confidence Medical Device Software Development. *Foundations and Trends in Electronic Design Automation*, Vol. 9, No. 4 (2015) 309–391.

2.5.4 Magazine Publication

- **Z. Jiang**, H. Abbas, K. Jang and R. Mangharam. Towards high confidence medical device software. *IEEE Computer* Jan 2016 Outlook

2.6 Awards

- Best Student Paper Award, 18th IEEE Real-Time and Embedded Technology and Applications Symposium (RTAS), April 2012
- Best Paper Award Nominee, Tools and Algorithms for the Construction and Analysis of Systems (TACAS), March 2012
- 1st Prize(Award of Excellence) of High-tech Medical Service, The World Embedded Software Contest (WESC), December 2012
- Best in Session Award, SRC TECHCON 2014, Sep 2014