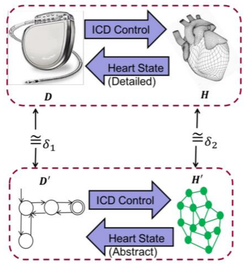
Invariant Extraction from Virtual Heart Models

A. Porter (UMD PI & Director), M. Lindvall (Fraunhofer PI), S. Huang, M. Diep, R. Cleaveland, NSF CNS 1446583
aporter@cs.umd.edu, mikli@fc-md.umd.edu, srhuang@cs.umd.edu, MDiep@fc-md.umd.edu, rance@cs.umd.edu

Model-Based Approach for Heart Models



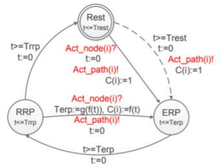
A. Islam, et al., CyberCardia Project: Modeling, Verification and Validation of Implantable Cardiac Devices, IEEE International Conference on Bioinformatics and Biomedicine (BIBM) 2016

- Aims to create an *in silico* design methodology for cyberphysical systems, such as medical devices
- Model-based approach – Handle complexity through abstract, composable models
- Overall success depends heavily on the quality of the underlying models
  - Requires both verification and validation
  - Models become a key source of knowledge/insight

Understanding and Comparing Heart Models

Research questions: Can we extract information from heart models using lightweight, model-based approach

- Present information capable for facilitating understanding for human users
- Generalize the approach toward different models



Portion of an automaton model for a heart

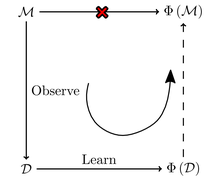
Q: Does a model such as the one to the left exhibit certain properties we need?

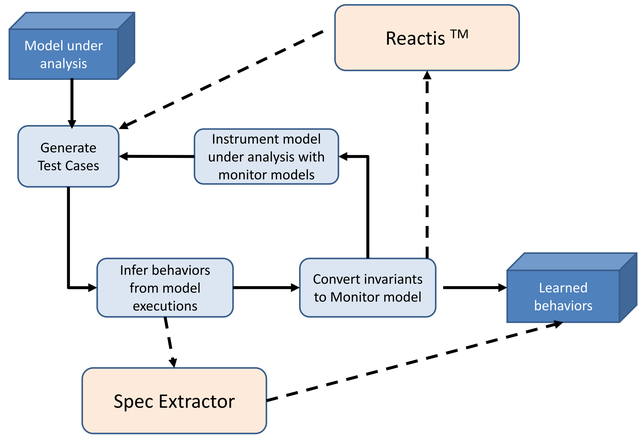
```
prevTRRP_cur == One ->
  Active == NotActive

inActive == NotActive & prevState == ERPState &
prevTRRP_cur == Zero ->
  State == RestState
```

Invariants inferred from the automaton

Automatic Invariant Inference of Models

- Given: A CPS system as a model M
- Goal: Identify properties from behavior of M (“likely invariants”)
  - Expressed as association rules
- Current methodology
  - Iteratively generate test cases and mine for learned behaviors (invariants)
  - Compare actual with learned behaviors



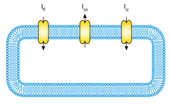


C. Ackerman, et. al., Automatic Requirement Extraction from Test Cases. RV 2010.

Case Study Overview

- Evaluate mined invariants against known properties of the heart
- Goal: identify invariants that are ultimately useful to an expert/researcher

- Investigating models of the heart
  - **Classify configurations**: Can we infer what parameters in a heart model (e.g., REST, ERP, RRP) result in normal, tachycardia (abnormally fast), and bradycardia (abnormally slow) heart rhythms?
  - **Model comparison/alignment**. Can we apply our approach to relate heart models that were developed using different approaches? Can invariants extracted from one heart model be compared with invariants extracted from another heart model? *(Work in progress)*



F. Fenton and A. Karma, “Vortex dynamics in three-dimensional continuous myocardium with fiber rotation: Filament instability and fibrillation,” Chaos 8, 20 ~1998.

Zhihao Jiang, Miroslav Pajic, Rajeev Alur, and Rahul Mangharam, “Closed-loop Verification of Medical Devices With Model Abstraction and Refinement”, Sept. 2013.

- Currently using MATLAB/Simulink models from literature

Case Study Overview

SA_REST = 300, SA_ERP = 150, SA_RRP = 100

t	SA_ACTIVE	AV_ACTIVE	SA_TIME	AV_TIME
854	0	0	NA	NA
855	0	0	NA	NA
856	1	0	552	NA
857	0	0	NA	NA
858	0	0	NA	NA

...

t	SA_ACTIVE	AV_ACTIVE	SA_TIME	AV_TIME
1407	0	0	NA	NA
1408	0	0	NA	NA
1409	1	0	552	NA
1410	0	0	NA	NA
1411	0	0	NA	NA

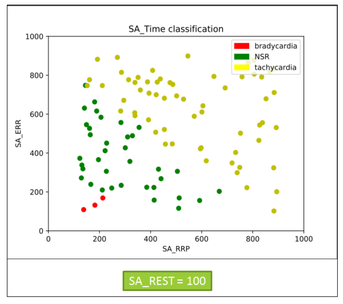
...

t	SA_ACTIVE	AV_ACTIVE	SA_TIME	AV_TIME
1960	0	0	NA	NA
1961	0	0	NA	NA
1962	1	0	552	NA
1963	0	0	NA	NA
1964	0	0	NA	NA

$SA_{ACTIVE} = 1 \wedge AV_{ACTIVE} = 0 \rightarrow SA_{TIME} = 552$

Heart rate is 1 per 552 ms; or ~108 bpm

Normal rate	SA_TIME >= 500, SA_TIME <= 1000
Slow heart rate	SA_Time > 1000
Fast heart rate	SA_Time < 500



References

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- Huang S. Learning Temporal Invariants from Data Stream. PhD diss. 2020