CyberCardia: Compositional, Approximate, and Quantitative Reasoning for Medical CPSs

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CyberCardia

Stony Brook University

CyberCardia @ Stony Brook

At Stony Brook, we are tackling three main problems: **reachability analysis, whole heart reconstruction and and ICD attacks.**

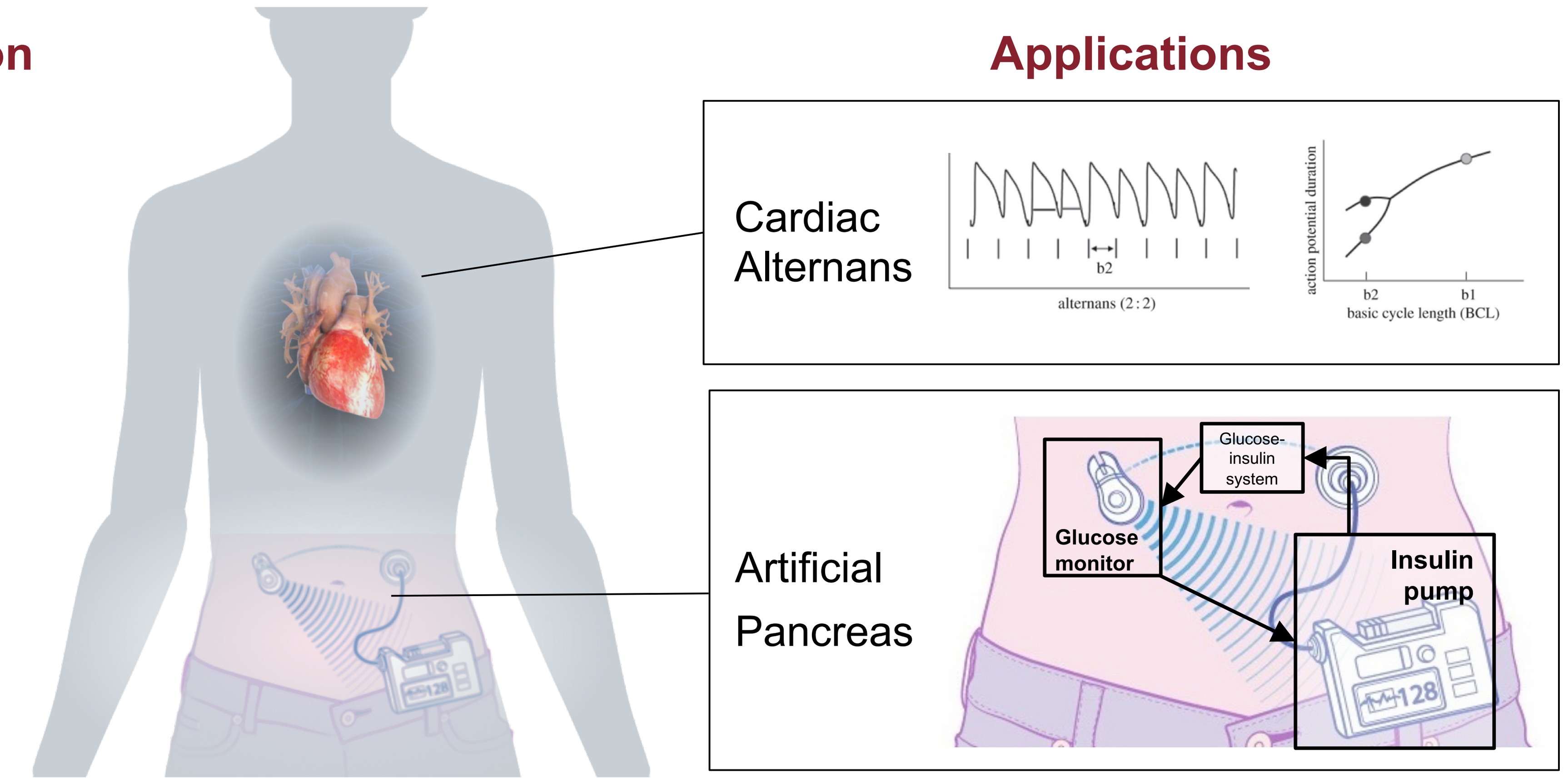
CyberCardia: advancing the state-of-the-art in medical CPSs

- The CyberCardia project aims to **advance in the state of the art for system verification and medical therapies** based on the use of **formal methods and closed-loop control and verification**.
- The animating vision for the work is to enable the development of a true *in silico* design methodology for medical devices that can be used **to speed the development of new devices** and to **provide greater assurance** that their behavior matches designer intentions, and to pass regulatory muster more quickly so that they can be used on patients needing their care.
- The acceleration in medical-device innovation achievable as a result of the CyberCardia research will also have long-term and sustained societal benefits, as better diagnostic and therapeutic technologies enter into the practice of medicine more quickly.

CPS modeling, verification & control techniques

- *Stochastic hybrid systems*
- *Data-driven modelling*
- *Reachability analysis*
- *Robust control*
- *SMT solving*

Applications



Lagrangian Reachability

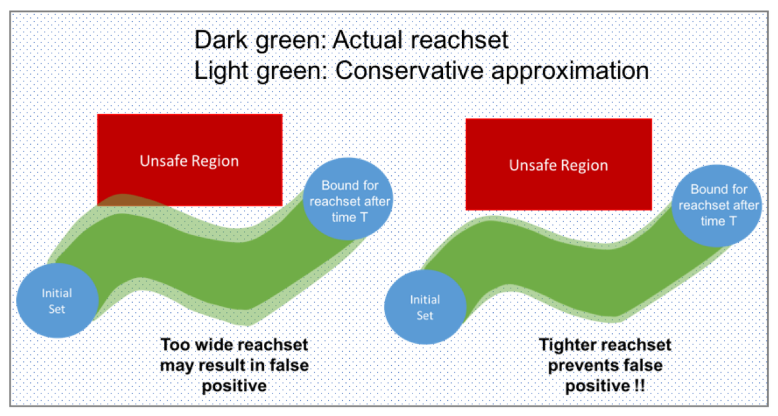
Reachability Analysis

- We study nonlinear, time-variant ordinary differential equations (ODEs):

$$\dot{x}(t) = f(t, x(t)), \quad x(0) = x_0$$

where $x: \mathbb{R}_{\geq 0} \to \mathbb{R}^n$ and f is analytic, so solutions are smooth trajectories in $\mathbb{R}^n$

- Goal: Compute reachtube overestimate that bounds the set of ODE trajectories originating in an infinite set of initial states



Continuous-Time Lagrangian Reachability

- Compute over-estimate for the gradient of the solution-flows
- Compute an optimized norm matrix analytically and over-estimate for Cauchy-Green (CG) deformation tensor from the computed gradient
- Compute an upper bound for the CG stretching factor Λ, then the ball over-estimate at time t_1 is $B_{M_1}(\phi_{t_0}^{t_1}(x_0), \Lambda.\delta_0)$
- Compute over-estimate $B_{M_0}(x_0, \Delta_0)$ for $[t_0, t_1]$ interval by bloating $B_{M_0}(x_0, \delta_0)$ where $\Delta_0 - \delta_0$ is computed based the maximum magnitude of the vector field in the interval

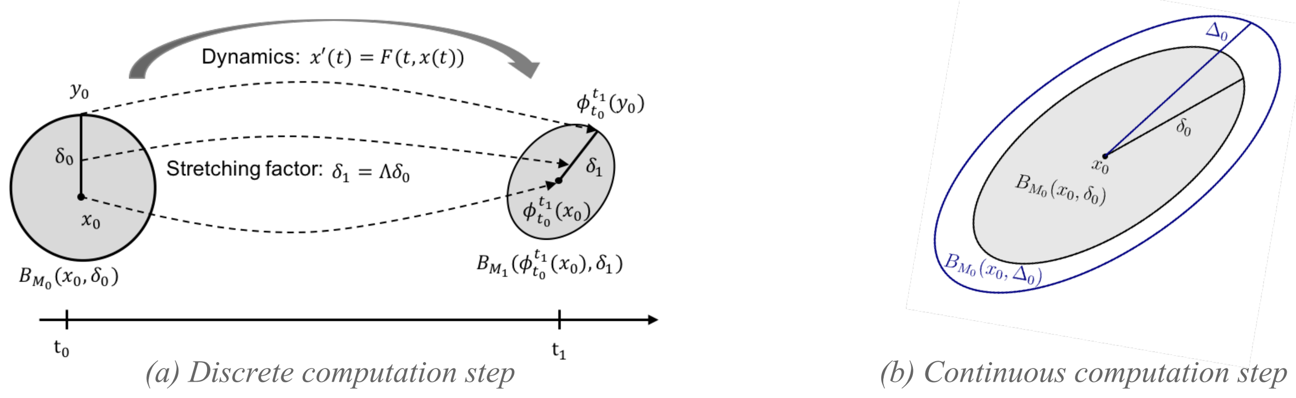
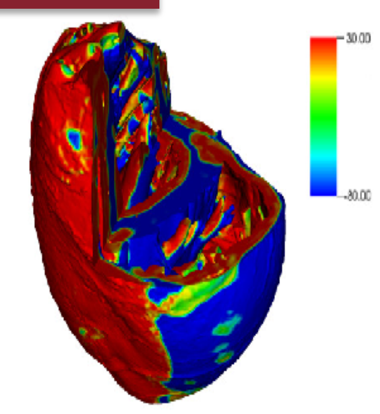


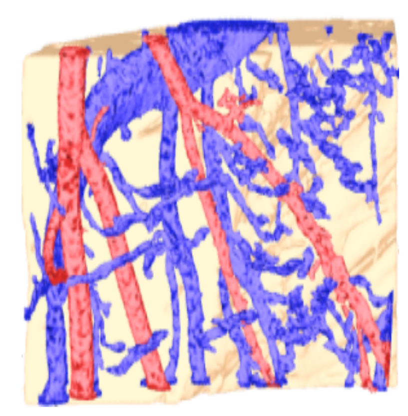
Illustration of the algorithm

Automated Construction of Whole Heart from MRI

1. Gray scale to black/white
2. Smooth boundary mesh
3. Outer blood vessel wall
4. Volume mesh

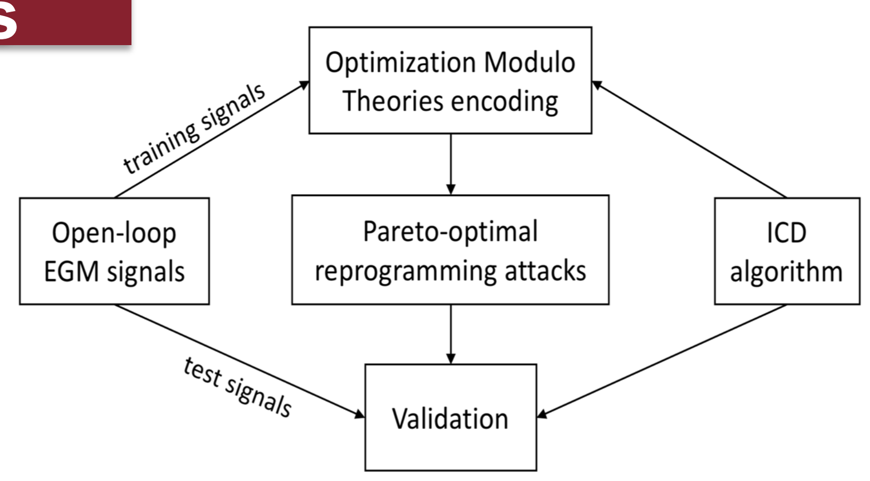
Public domain + new algorithms

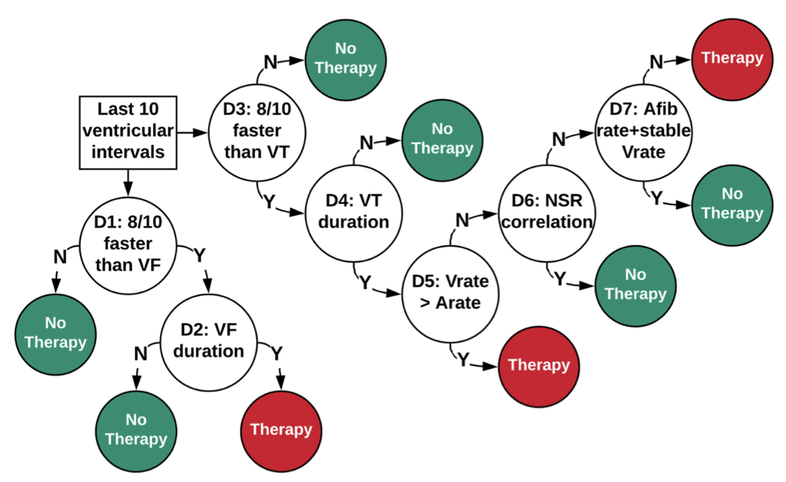




Stealthy Reprogramming Attacks on Cardiac Devices

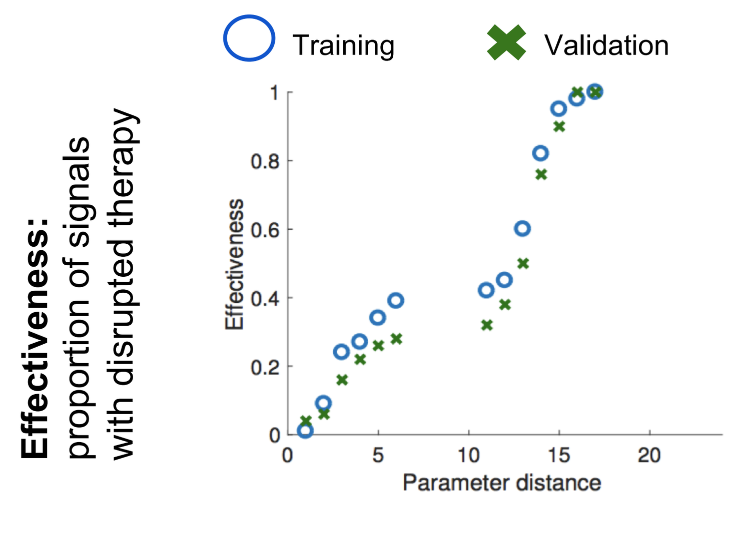
- Reprogramming attacks alter ICD parameters to compromise therapy
- Previous work and FDA recalls show that unauthorized access is possible
- **First systematic method to synthesize stealthy attacks on cardiac devices** (model-based)
- Finds attacks with optimal effectiveness-stealthiness tradeoff WRT a set of EGM signals
- Uses synthetic EGMs to tailor attacks to victim's condition
- Evaluated on model of Boston Scientific's VT/SVT discrimination algorithm



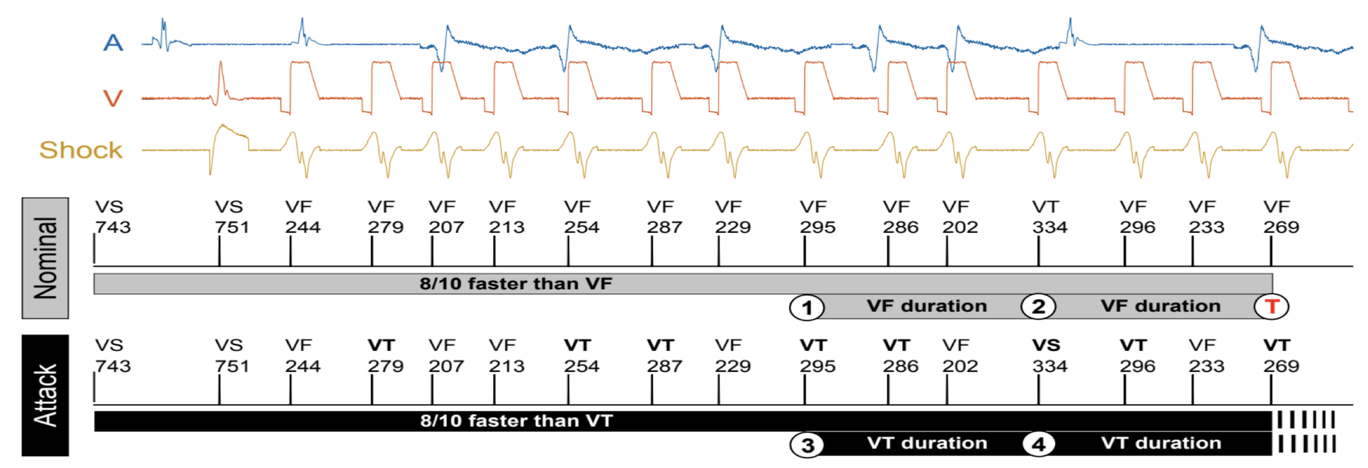


Boston Scientific RythmID Discrimination Algorithm

Condition-specific Pareto-optimal attack parameters (x19 conditions)



Stealthiness: distance to nominal ICD parameters



Example of synthesized attack preventing required therapy

References

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[2] Paoletti, N., Jiang, Z., Islam, M. A., Abbas, H., Mangharam, R., Lin, S., Gruber, Z., Smolka, S. (2018) Synthesizing Stealthy Reprogramming Attacks on Cardiac Devices. *arXiv preprint arXiv:1810.03808*(2018)

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