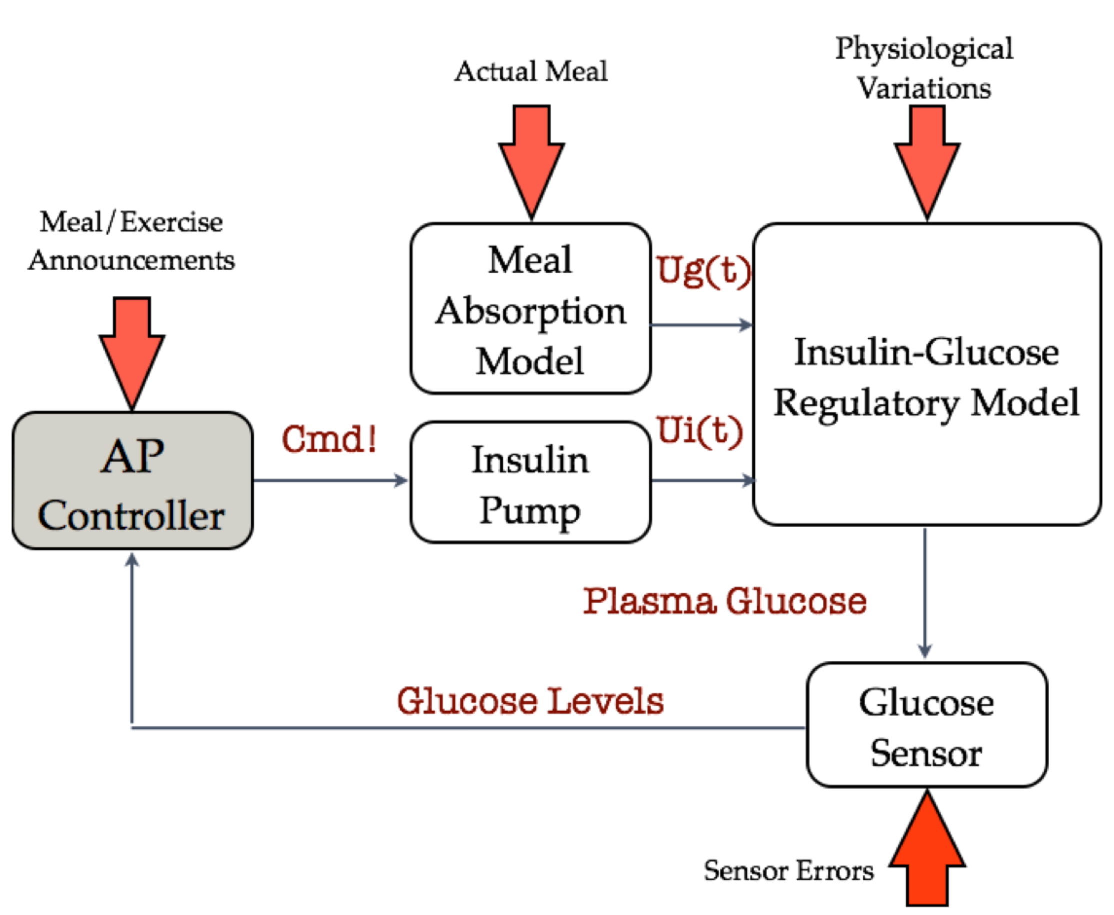
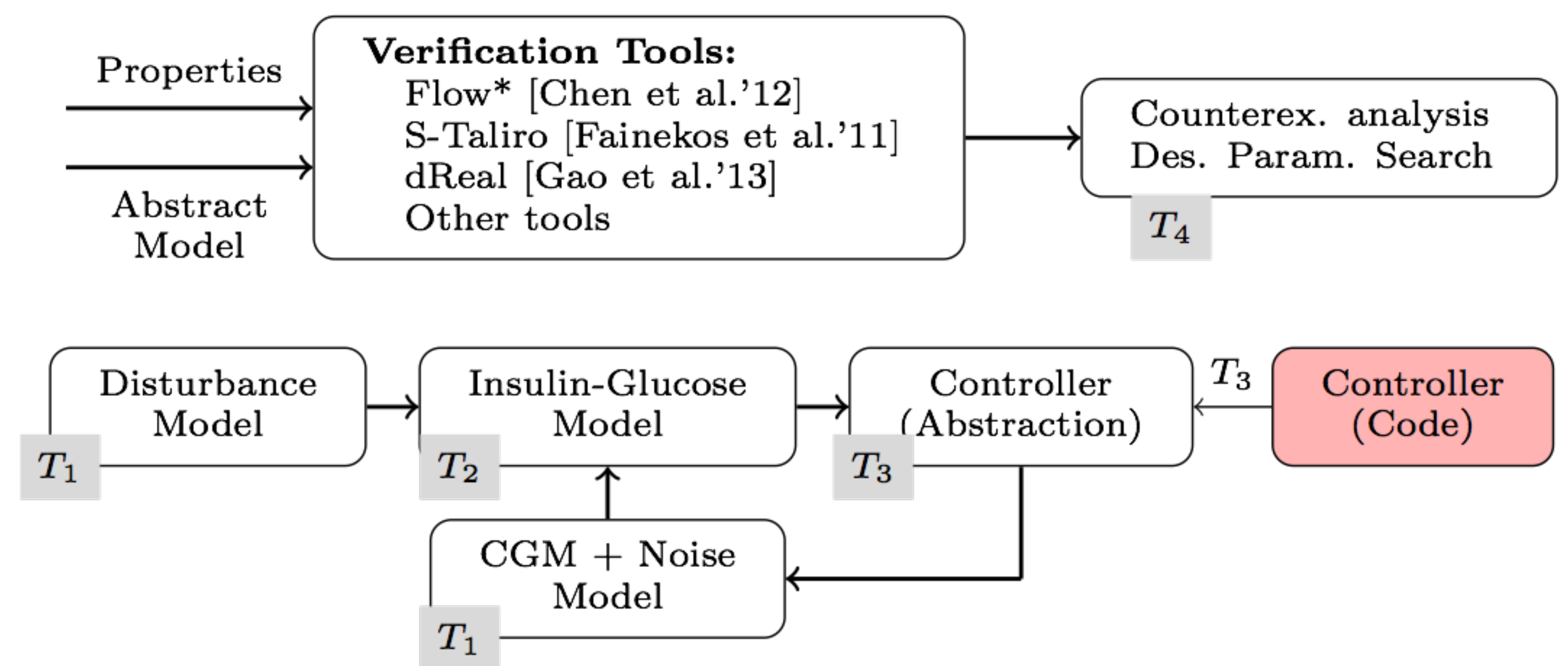
Synergy: In-Silico Functional Verification of Artificial Pancreas Control Algorithms

Sriram Sankaranarayanan, David Bortz, Shalom Ruben; David Maahs; Faye Cameron and B. Wayne Bequette
University of Colorado, Boulder; Stanford University Medical School; and Rensselaer Polytechnic Institute

The artificial pancreas (AP) is a set of increasingly sophisticated devices and algorithms that will automate the delivery of insulin to patients with type-1 diabetes. While the AP concept promises to alleviate the burden posed by the self-management of blood glucose levels, it also poses significant risks arising from a combination of external disturbances such as patient meals, physical activity, sensor errors, network delays and physiological variations. We are investigating modeling and verification frameworks that allows designers of AP control algorithms to automatically evaluate their designs against a large number of disturbance patterns. The project will investigate disturbance modeling techniques from data, delay-differential models of insulin-glucose dynamics, control code abstraction and techniques for explaining verification results to clinical researchers and control engineers.



Components of an *in-silico* closed-loop Artificial Pancreas System.



Verification Framework	
Input:	Control algorithm (Matlab syntax) + Specification
Output:	*Post-processed* violations.
Time Bnd:	24 hrs (full day)

Project Objectives

Verification of artificial pancreas control software with patient models.

- *Disturbance modeling*
  - Sensor disturbances.
  - Patient behavior.
- *Patient modeling*
  - Data oriented modeling of human insulin-glucose physiology.
  - Delay differential equation models.
- *Root Cause Isolation*
  - Automating the isolation of root causes for falsifications.

Project Outcomes

Case studies on existing control implementations.

- PID-based control algorithm [Weinzimer et al. '08].
  - Late stage clinical trials.
- Hypo/Hyper mitigation controller [Cameron et al.'12].
  - Outpatient clinical trials.

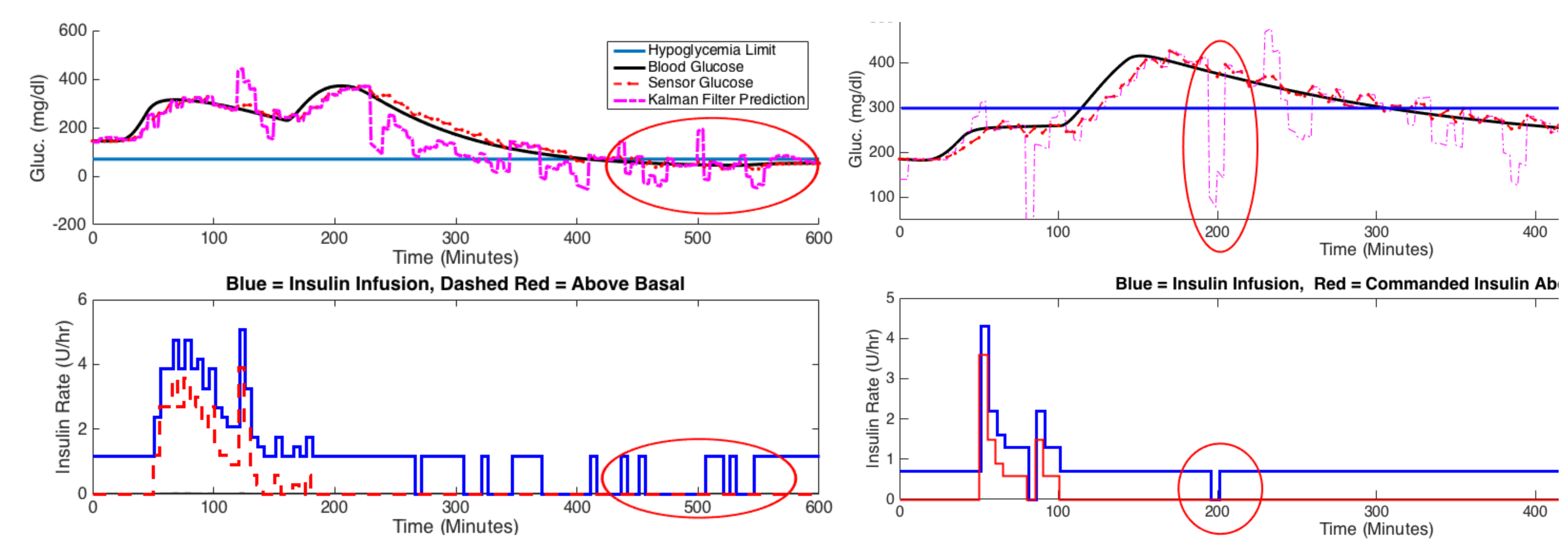
Automatic root-cause isolation techniques.

Development/Improvement of disturbance models.

- Model of human meal patterns using NIH dataset.
- Modeling pressure induced sensor attenuation [Baysal et al.14]

Development/Improvement of personalized patient models.

- Delay Differential Models [Kissler et al.'14, Bortz et al.'16]
- Data oriented models for human insulin physiology.



Violations discovered by our analysis: (Left) showing insulin delivery resumption under hypoglycemia, and (Right) suspension under hyperglycemia.

Selected Publications

[1] Sankaranarayanan et al., *Model-Based Falsification of an Artificial Pancreas Control System*. In ACM SIGBED Review (Special Issue on Medical Cyber Physical Systems) (To Appear), 2016.

[2] Forlenza et al., *Refining the Closed Loop in the Data Age: Research-to-Practice Transitions in Diabetes Technology (Editorial)* In Diabetes Technology and Therapeutics 17(5), (2015).

[3] Cameron et al., *Towards a Verified Artificial Pancreas: Challenges and Solutions for Runtime Verification.* Runtime Verification (RV'15) Lecture Notes in Computer Science Vol. 9333, pp. 3-17 (2015).

[4] Ruben, *Respect the Implementation, American Control Conference (2016).*

[5] Bortz. *Characteristic Roots for Two-Lag Linear Delay Differential Equations.* Discrete Continuous Dynamical Systems - B, 21(8), Oct. 2016.

[6] Xin Chen, and Sriram Sankaranarayanan, *Decomposed Reachability Analysis for Nonlinear Systems* In IEEE Real Time Systems Symposium (RTSS), to appear (2016).

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Principal Investigator Contact: Sriram Sankaranarayanan srirams@colorado.edu
Project web site: http://bit.ly/2eeaxXw