HyMn: Mining Linear Hybrid Automata from Input/Output Traces of Cyber-Physical Systems

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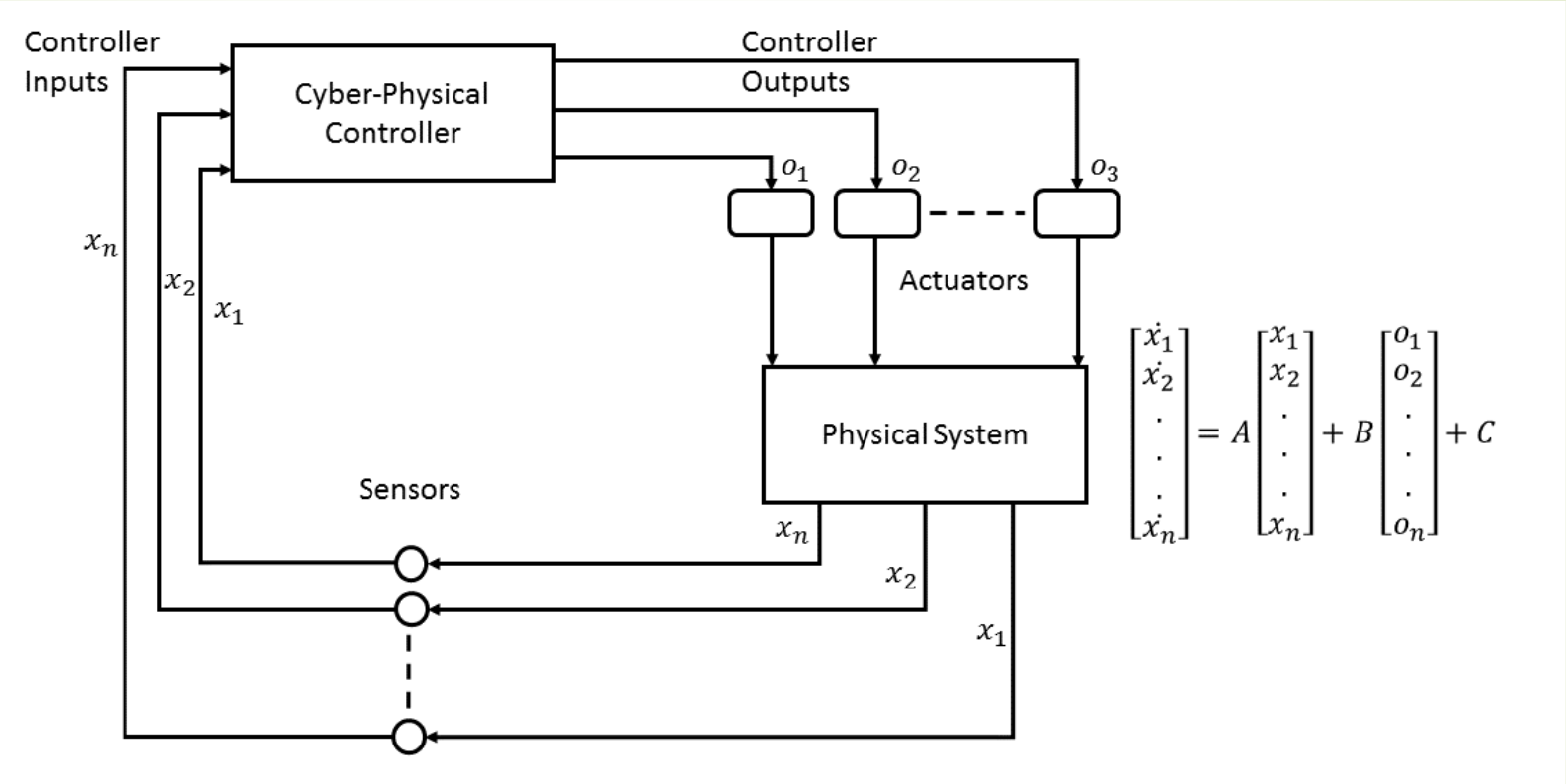
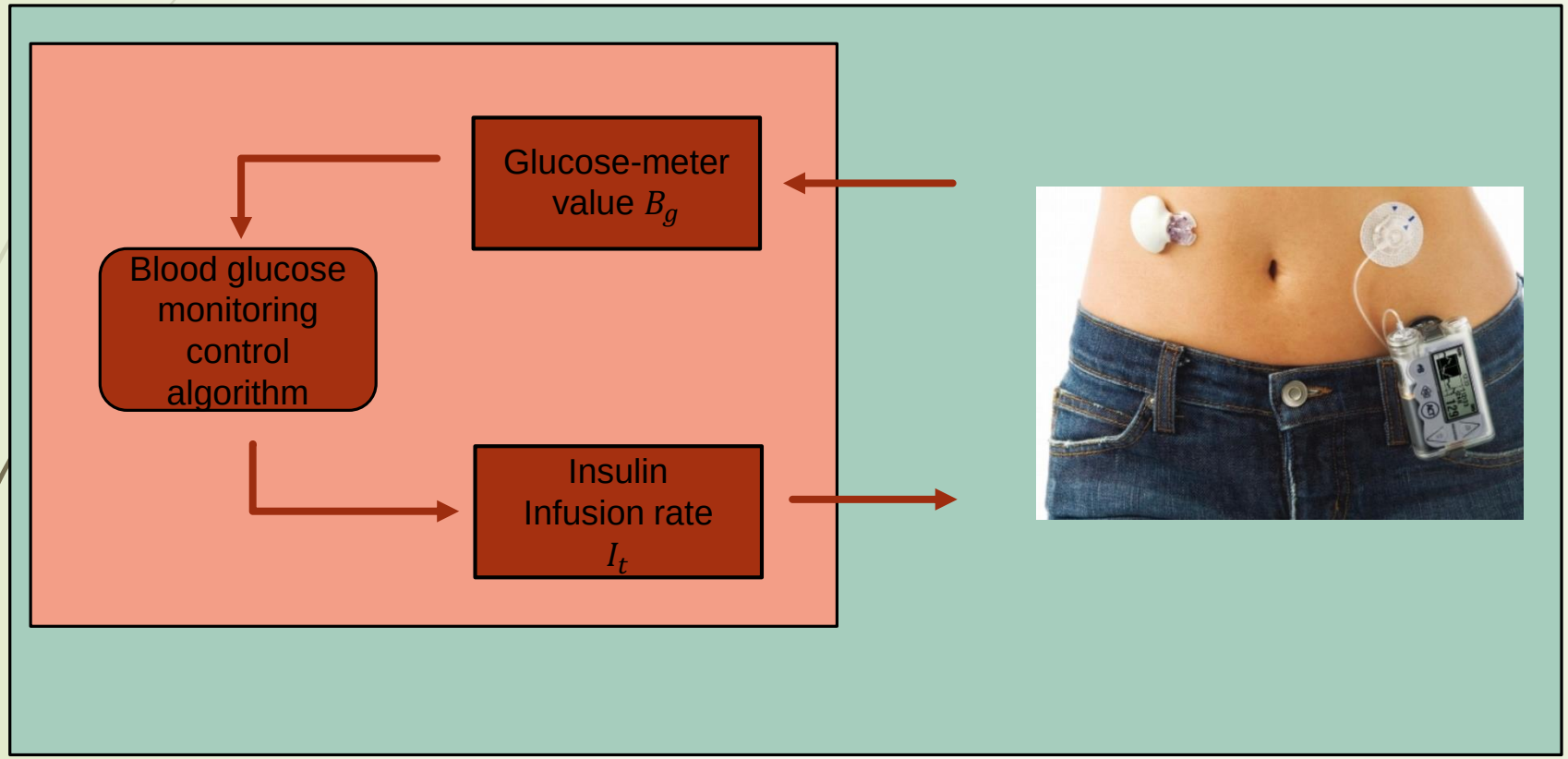
Introduction

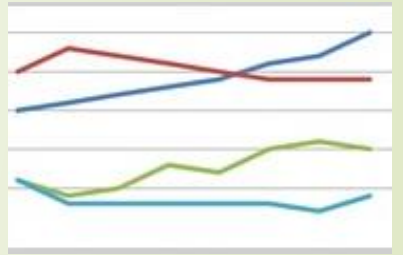
- Cyber-physical system (CPS) design and implementation has seen a new revolution of personalization.
- Medical CPS should be configured considering the unique parameters of the individual.
- CPS verification techniques should be equipped with capabilities for considering unique parameters of the physical system.
- One of the versatile tool used for CPS verification is reachability analysis.

System Model



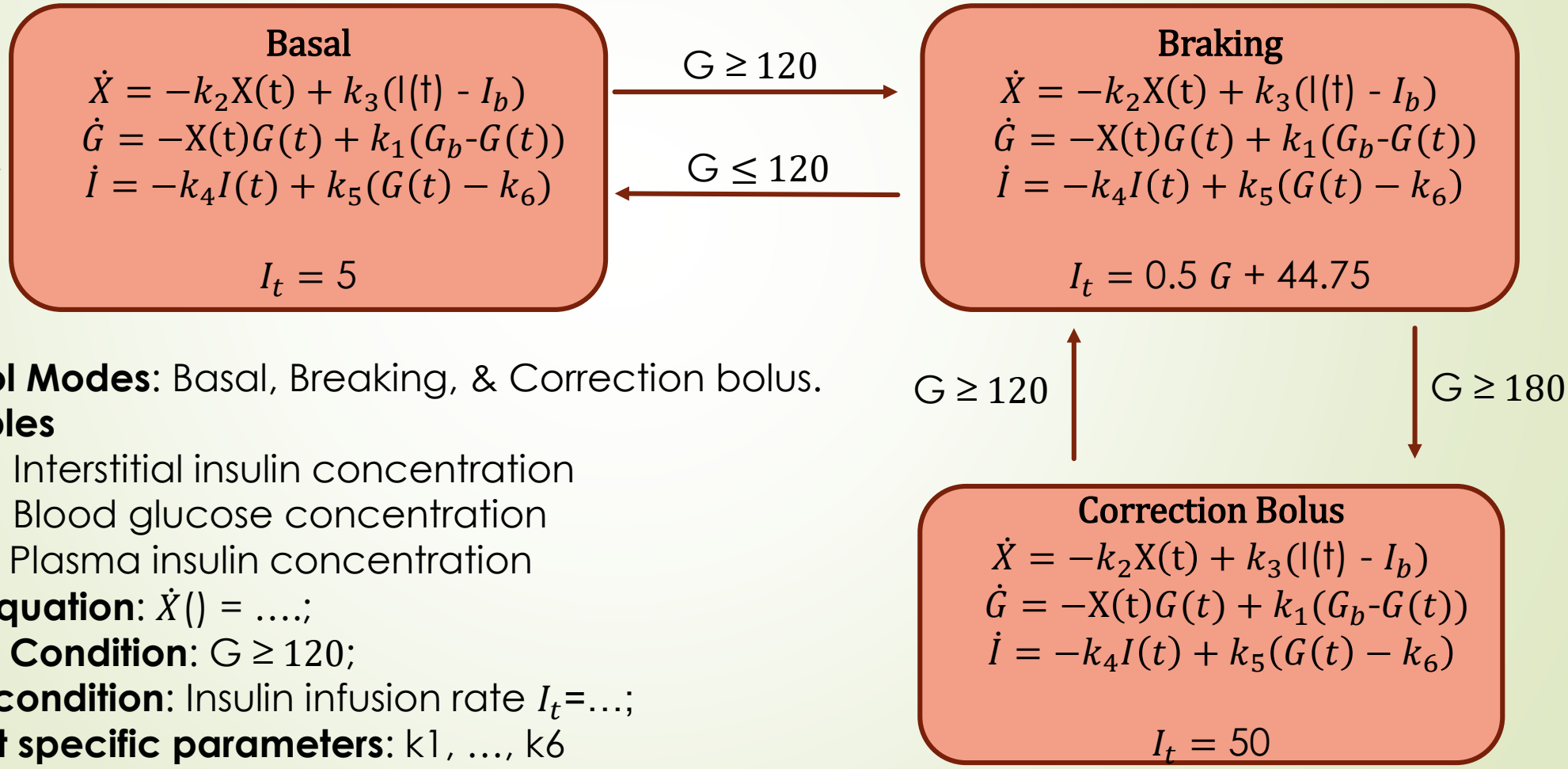
Example CPS: Artificial Pancreas (AP)





Input/Output Operation Traces

Example CPS: Hybrid automata of AP



Control Modes: Basal, Breaking, & Correction bolus.
Variables

X: Interstitial insulin concentration
G: Blood glucose concentration
I: Plasma insulin concentration

Flow Equation: $\dot{X}() = \ldots.$;
Guard Condition: G ≥ 120;
Reset condition: Insulin infusion rate I_t=…;
Patient specific parameters: k1, …, k6

Problem Statement

- From I/O traces collected from the operation of CPS, infer a hybrid automata (HA) representation of the system.
  - Infer linear flow equations representing the dynamics of the system, with patient-specific parameters.
  - Infer controller modes.
  - Infer guard and reset conditions.

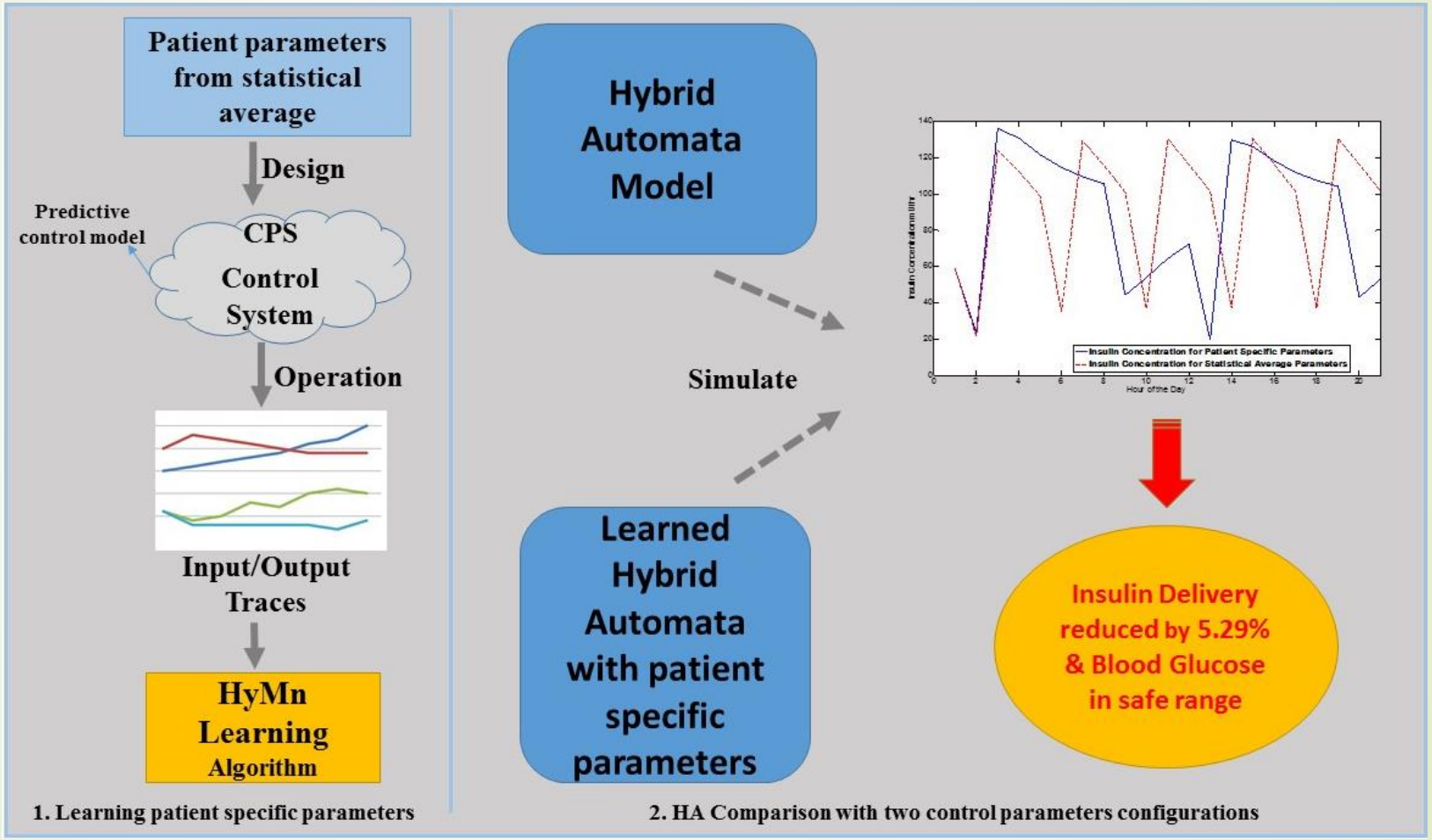
- HA – used for safety verification using reachability analysis
- Patient-specific parameters for improving operation of the controller

- Assumption: Linear hybrid systems, i.e. linear flow equations, linear guard conditions, noiseless traces.

Related Work

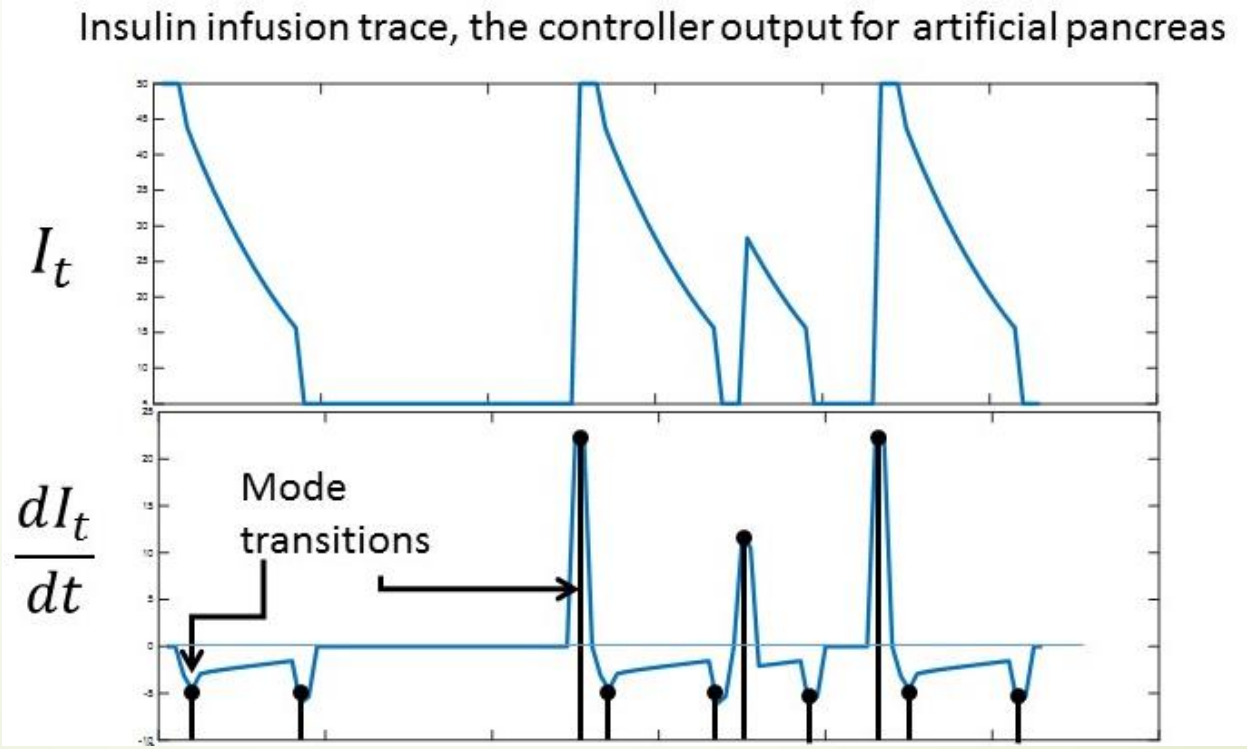
- SL2sX for translating a Simulink model to a hybrid automaton.
- Inferring a HA from an abstract state transition system.
  - We infer a hybrid automata from input-output traces.
- Inferring a HA for system that exhibits input changes in the form of step functions and the derivatives of the continuous state variables are constant.
- Inferring maximum-likelihood hybrid system model using only continuous output of the system. It assumes that guard conditions are independent of the continuous state.
  - Not observed in practice
- Learning hybrid automata from observed run-time behavior of the system using CHARDA.
  - Requires prior knowledge of model templates.

Proposed Approach: HyMn



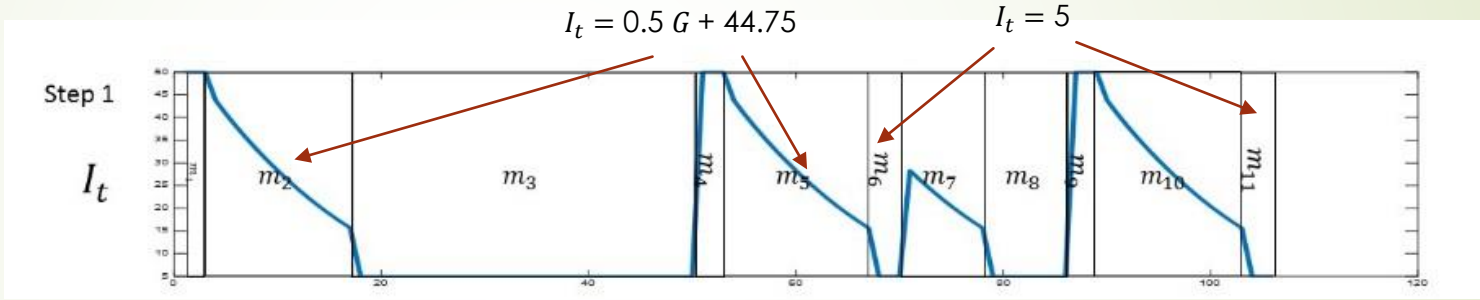
HyMn Algorithm

- **1- I/O segmentation**
  - Segment input/output traces considering times at which there is a potential discrete mode change.

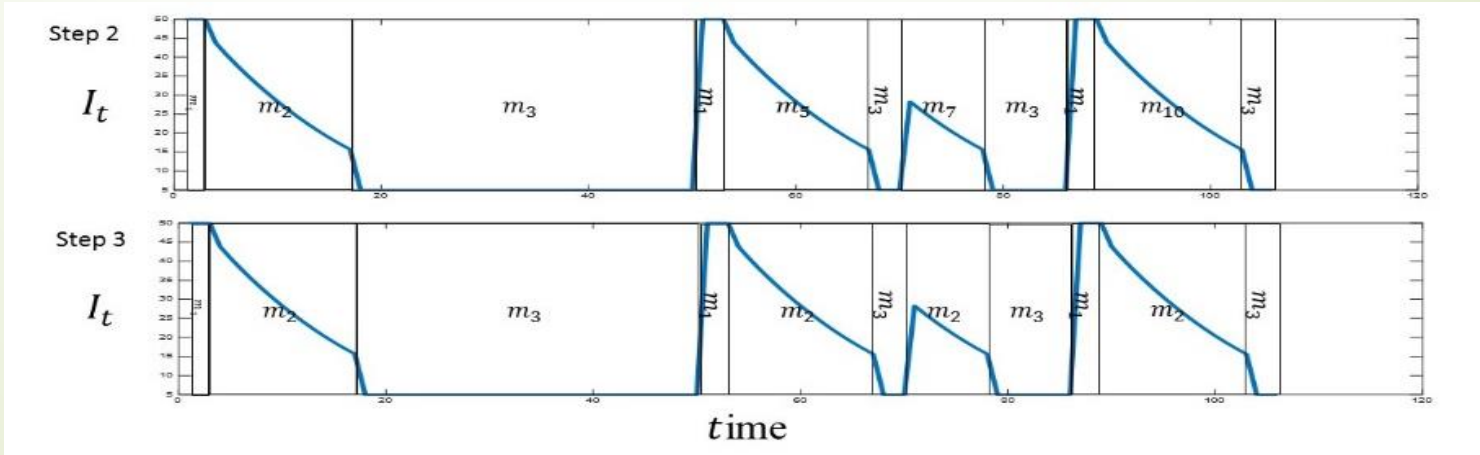


HyMn Algorithm

- **2- Mode Classification**
  - Derive linear equations connecting controller outputs to the inputs by applying Fisher Information and Cramer Rao Bound (CRLB) for each segment in the trace.



  - Cluster segments into equivalence classes corresponding to each controller mode.



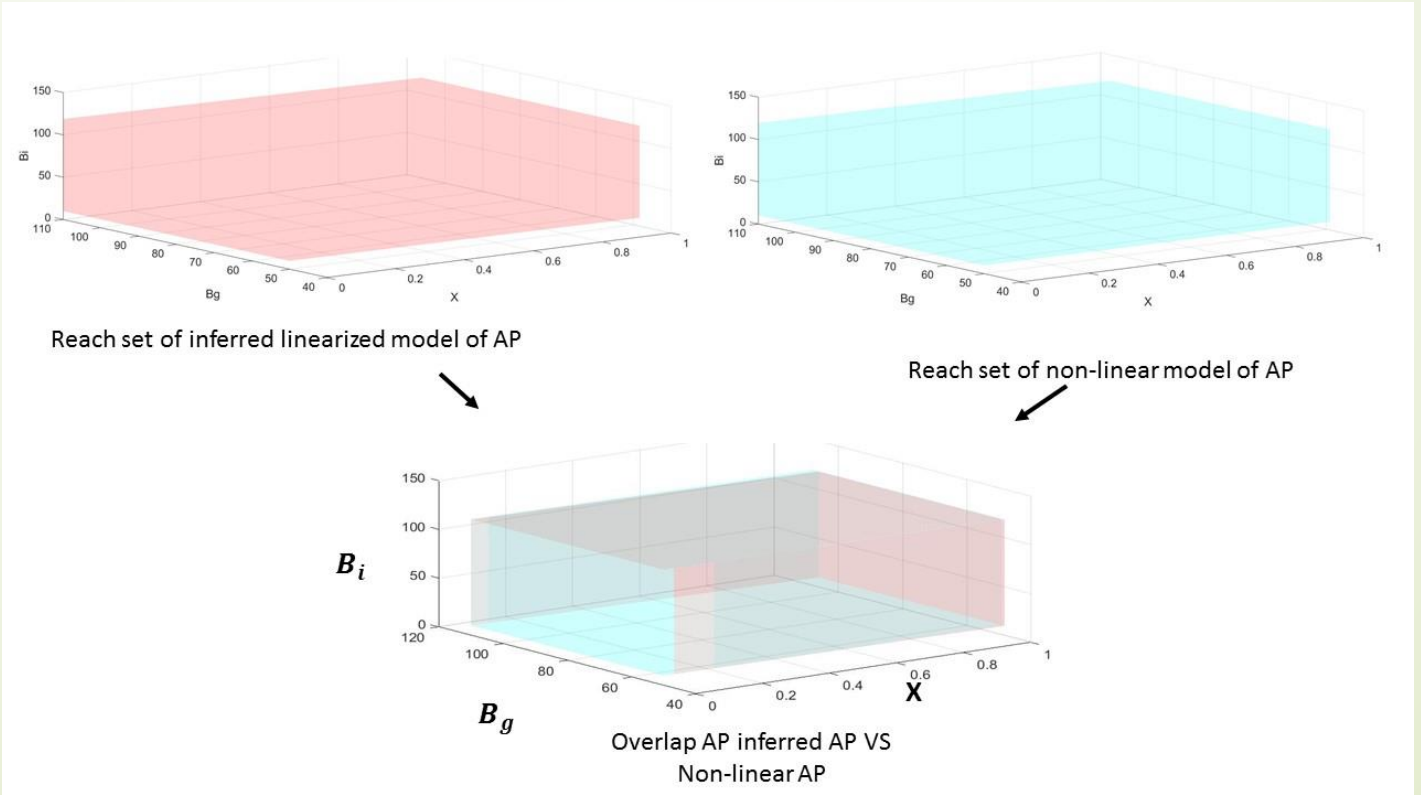
HyMn Algorithm

- **3- Flow Extraction**
  - For each mode, HyMn employs Fisher information and CRLB theorem to derive flow equations.
  - The output of this re-classification are unique modes of the hybrid system, where two modes may have different jump conditions or flow equations.

- **4- Guard Condition mining**
  - HyMn Employs Fisher information and CRLB to derive a linear combination between each continuous variable with the other variables at the time of the transition.

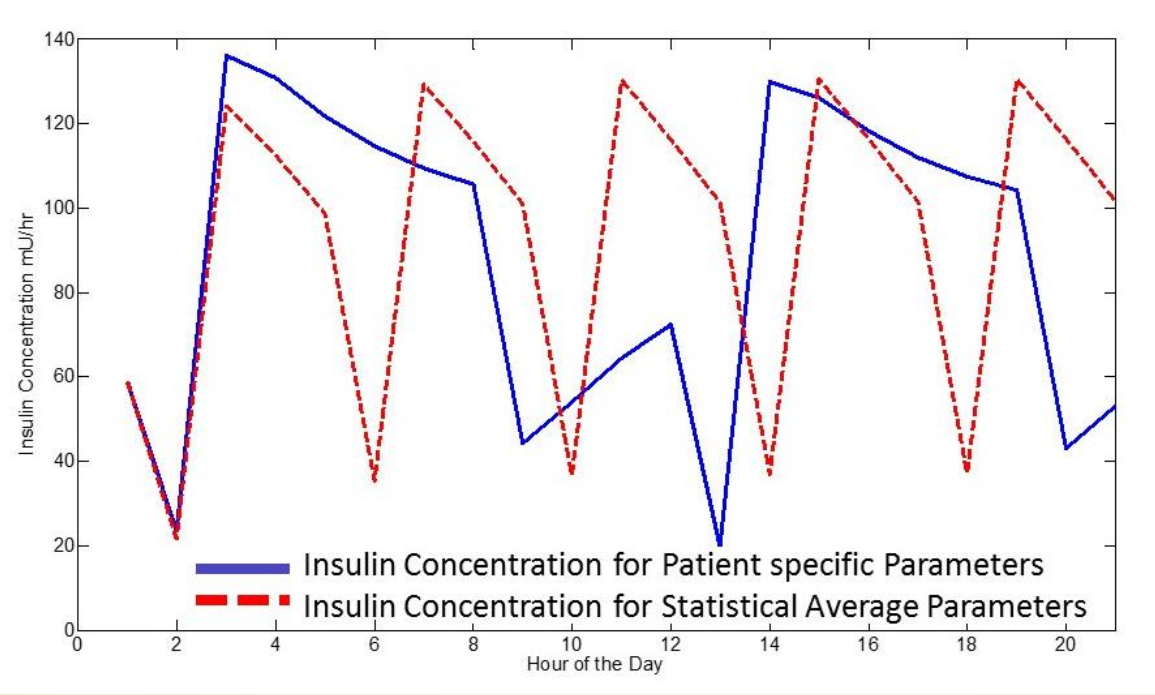
Safety Verification

- Apply HyMn to the traces of the AP control system and infer the hybrid system model of AP.
- Reach sets comparison of inferred and actual hybrid automata of AP using SpaceEx.



Evaluation

- We executed the AP control system with two parameter configurations:
  - Parameters obtained using average statistical estimates on data collected from individuals in real world scenarios.
  - The patient specific parameters learned using HyMN.
- We kept blood glucose profile the same for both configurations.



Insulin Delivery reduced by 5.29% & Blood Glucose in safe range

Conclusions & Future Work

- The HyMn algorithm presented in this paper can extract linear hybrid systems from I/O traces of a CPS.
- The key innovation:
  - Controller output and guards are linear combination of the continuous state variables.
  - Flow equations are a set of linear differential equations.
- Issue: the accuracy of inferred hybrid system depends on the length of observation of the I/O characteristics of the control system.

Questions & Answers