Formal Models of Human Control and Interaction with CPS

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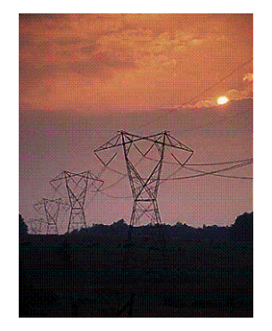
Motivation

Analysis and Design of Human-CPS



- Formal analysis for
  - Characterization
  - Prediction
- Challenge of information asymmetry
  - Human knowledge of environment that the automation may lack
  - Automation knowledge of CPS states that the human may lack
- Cognitively plausible analytic model of the human operator
- Integration of cognitive model and hybrid dynamical system model
- Verification with a human in the loop
  - Realistic operating environment
  - Model uncertainties
  - Cognitive limitations and abilities

Target Area: Science of CPS

- Multidisciplinary "synergy" project
  - Computer science
  - Control theory
  - Human factors and human-robot interaction
  - Cognitive psychology

Research Goals

1. Formally specified and validated models of human interaction with CPS under:

- Realistic operating conditions
- Human bounded rationality
- Human cognitive limitations

2. Analytic approaches to characterize and predict behavior of human-CPS

- Computational methods for high dimensional systems
- Likelihood of safety in stochastic systems
- Safety-based controller synthesis despite incomplete information about true state of the system

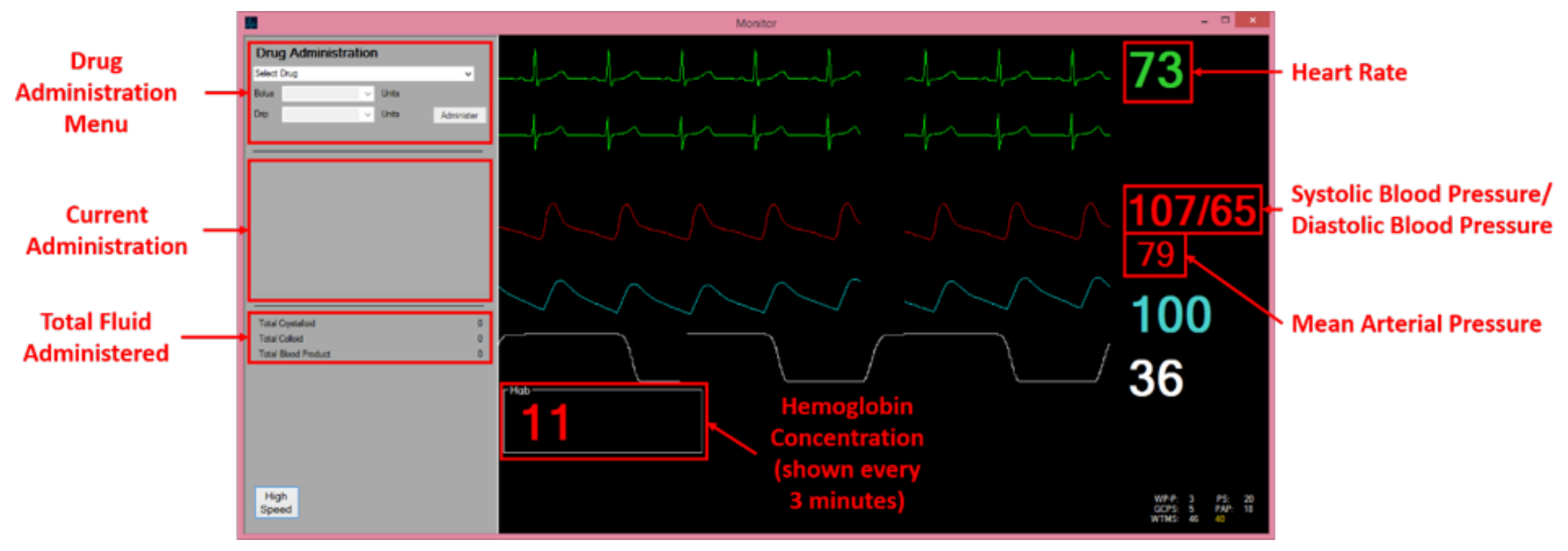
3. Abstract interface design that allows analysis of "safe" regions of operation

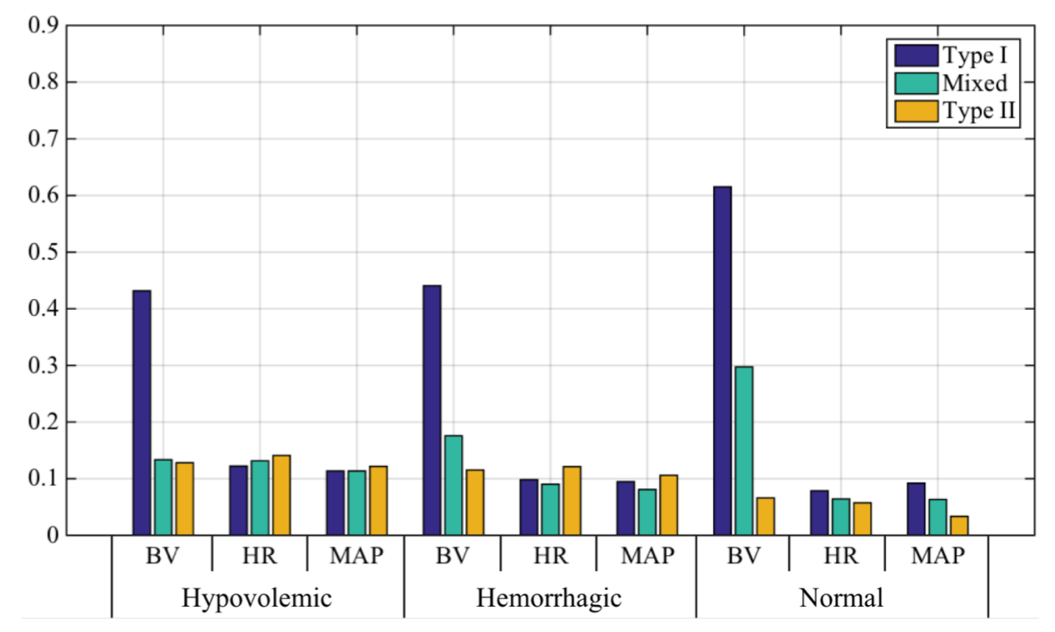
- Mathematical methods and computational tools for synthesis

Human Experiment for Fluid Management Task

Fluid Management Task in Critical Care

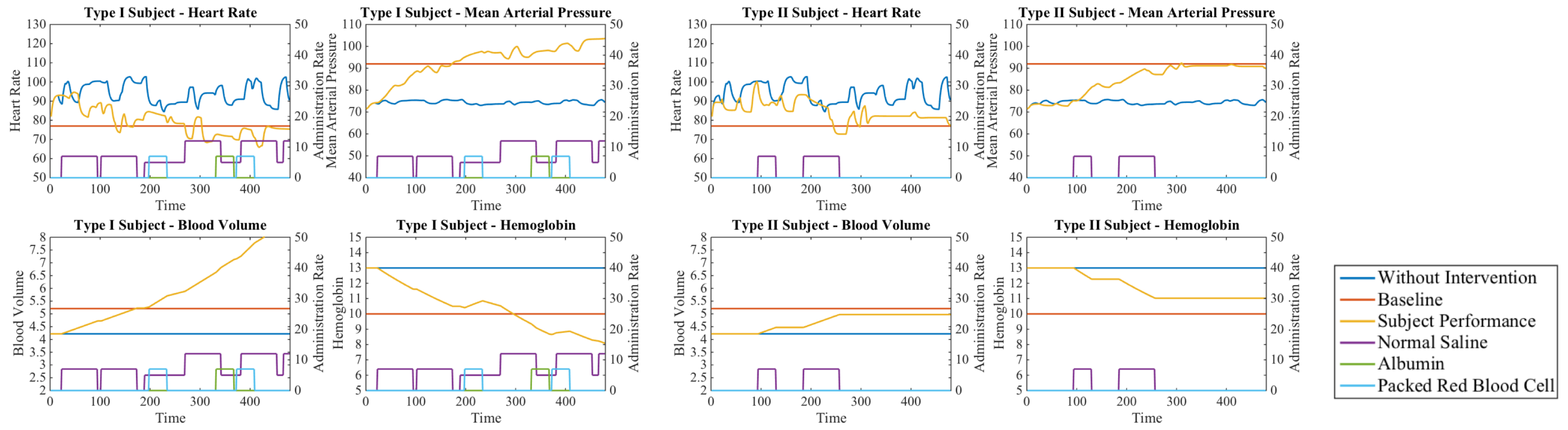
- **Goal:** Detect and compensate for loss of fluid due to dehydration (hypovolemic) or hemorrhagic shock on a Patient simulator, developed by Dr. Joe Rinehart, MD (Anesthesiology) at UC Irvine
- **Method:** Medical Fellows and naïve participants are asked to manage patients in 6 scenarios, developed by Dr. Matthew Siedsma, MD (Critical Care U of Pittsburgh), involving hemorrhagic and hypovolemic shock as well as control conditions (no action)





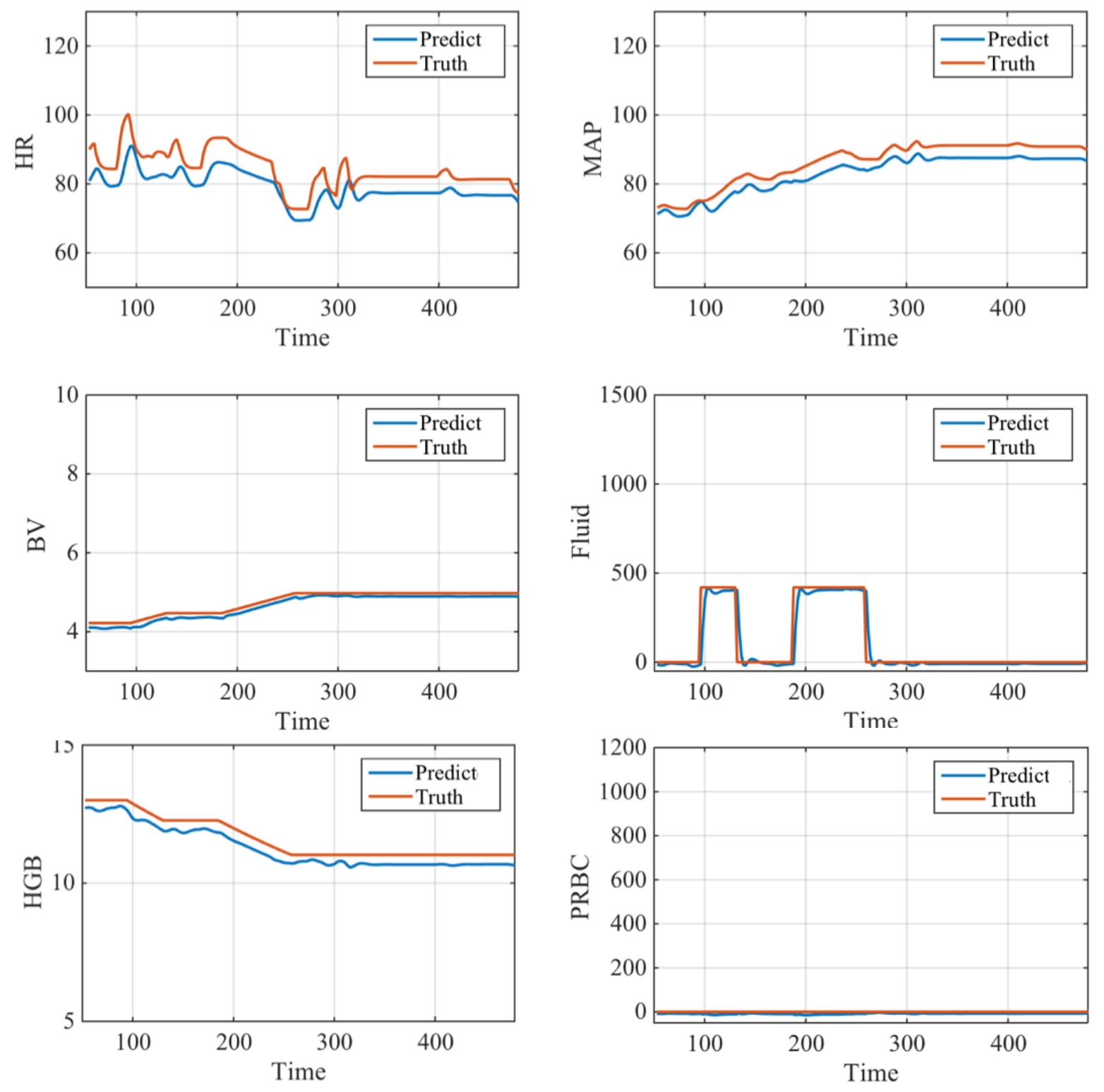
Human Experiment Results

- The subject performance metric was normalized root mean square (RMS) error from baseline of patient parameters, namely HR, MAP, and the hidden variable BV.
- Significant improvements were observed within each episode type for MAP, while there was no overall order effect for HR and BV.
- Subjects were categorized by their strategies. Type I subjects are more aggressive in terms of intervention. In contrast, Type II subjects are more conservative,
- In terms of *visible parameters*, all subjects are doing comparably well for BV measurement, Type II subjects achieve better performance than Type I subjects. Type I subjects over-administered fluid resulting in *excessive fluid (Blood Volume)* in the patient (very undesirable). In experiments with a limited number of medical Fellows, we observed that the Fellows acted like subjects of Type II.



Analytic Model for Cyber Physical System

- States consists of vital signs, and actions consists of amount and type of fluids given.
- The Cyber Physical System is modeled by a Recurrent Neural Network (RNN) with Long Short Term Memory (LSTM) architecture.
- The model is trained on data of all subjects for three scenarios, and is tested on subject data for the other three scenarios.
- Decent performance is achieved for one-step prediction.
- The LSTM models can be used for analysis on the viability and reachable set in the Cyber Physical System.



Validation of CPS Model

ACT-R Cognitive Model and Model Validation

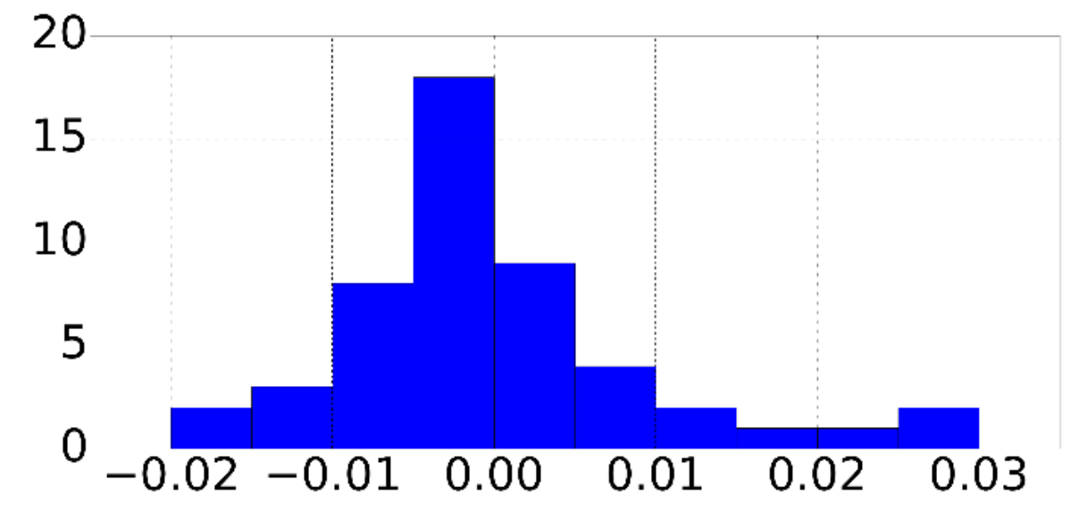
- Abstraction of ACT-R Cognitive model to Markov control input

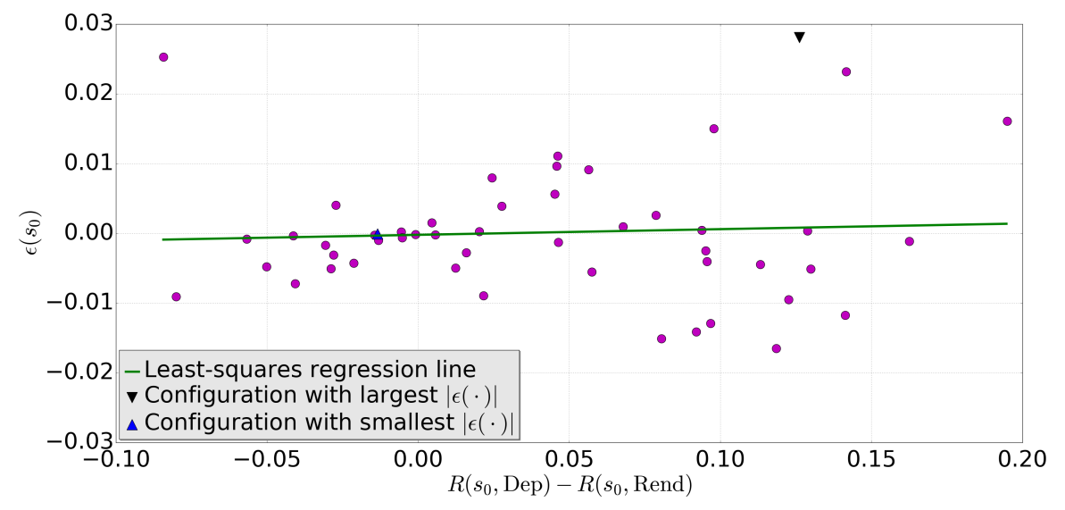
$$u_h = \pi_h(s_0)$$

- Comparison of expected outcome via forward stochastic reachable set with actual data

$$R(s_0, u_h) = \frac{m(SensedS(s_0, u_h))}{m(\mathcal{A})} \qquad \mathbb{E}[R(s_0, u_h)] = \sum_{u_h \in \mathbb{U}_h} \mathbb{P}\{u_h\} R(s_0, u_h)$$

- Validation of Markov model of human input
- ACT-R and human subjects have similar expected outcome (t-test with p=0.98)
- No statistical correlation for any initial condition





Forward Stochastic Reachability Analysis

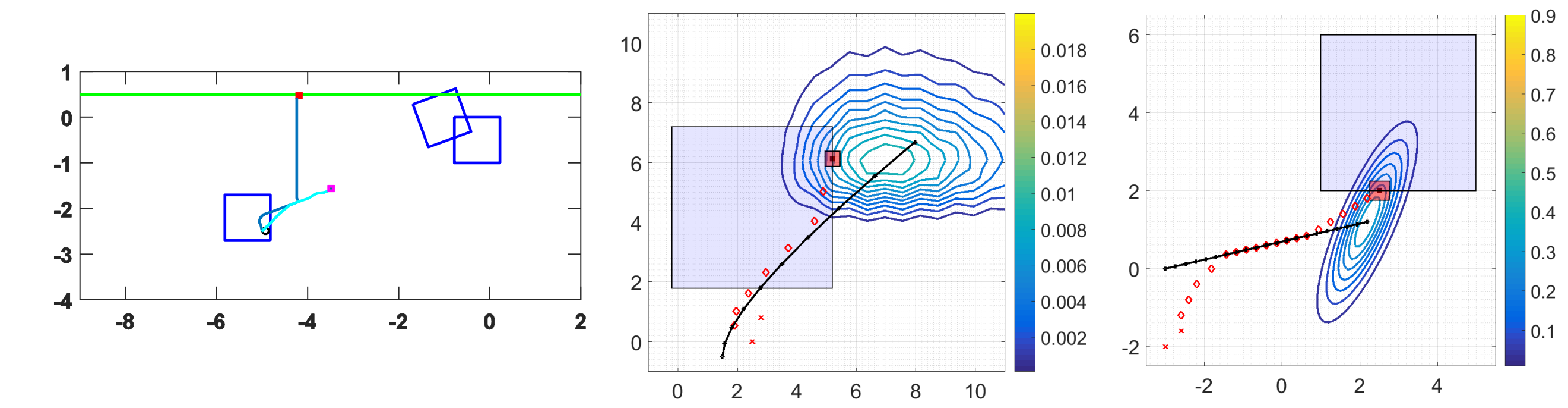
- Uncontrolled, nonlinear dynamical systems
- Forward stochastic reach probability measure and its support
- Iterative expressions for the forward reachable sets and forward reachable densities for nonlinear systems

$$\psi_x[\bar{y}; t+1] = \left(\psi_{f(x)}[\cdot; t] * \psi_v[\cdot]\right)[\bar{y}]$$

- Analytical expressions via Fourier transform for linear systems

$$\psi_x(\bar{y}; t+1) = \mathcal{F}^{-1}\{\exp(j\bar{\alpha}^\top (A^t x_0))\Psi_W(C_{n\times(tp)}^\top \bar{\alpha})\}(\bar{y})$$

- Analysis applicable to
  - Obstacle avoidance problems where robust control fails
  - Pursuit problems of a stochastically moving target
- Convexity assured for LTI systems with log-concave distributions



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