Formal Models of Human Control and Interaction with CPS

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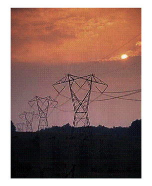
Motivation

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

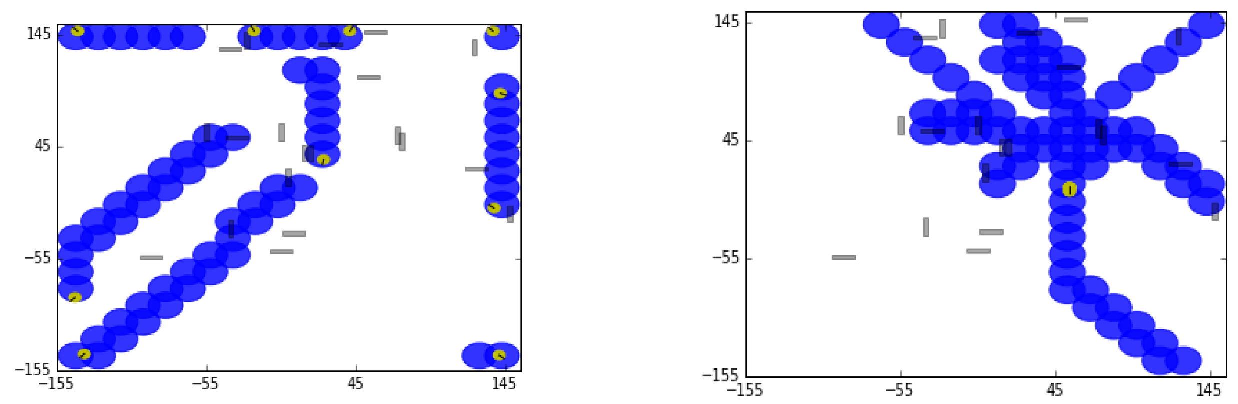
Modeling Human Decision Making

Method

- Instance-based task-general cognitive models of control (ACT-R)
- Abstraction from cognitive models to task-specific analytical models

Example Task: Maximizing Coverage with a Robot Swarm

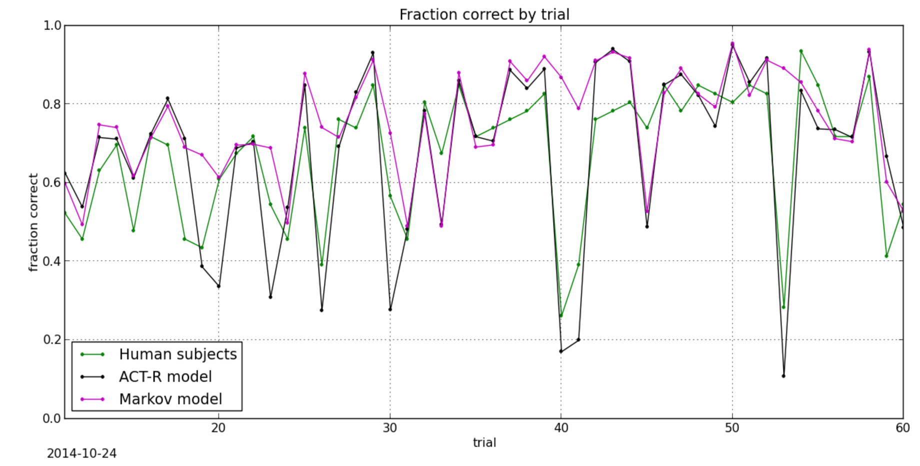
- What is the likelihood of maximizing coverage, given a suite of vehicle dynamics as well as likelihood human choice?
- What information about the stochastic reachable and viable sets should be abstracted for presentation to the user?
- Deployed on Amazon Turk
  - 60 users to date
  - Series of 20 experiments
  - Data recorded for cognitive model

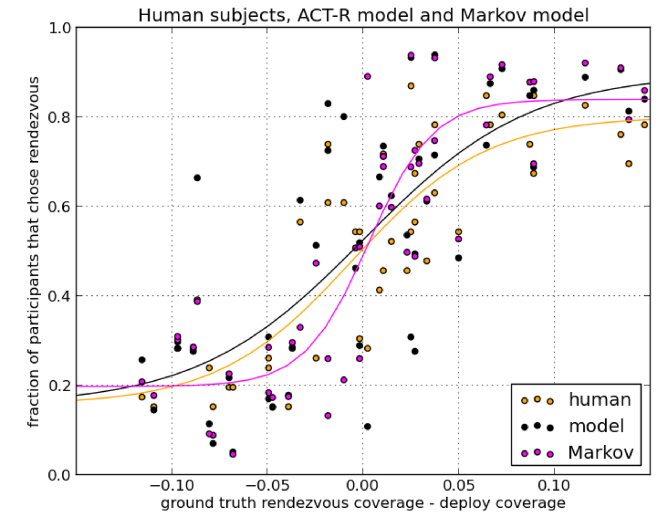


Example problem: Comparison of area coverage when applying two different exploration strategies for the complete duration of the mission. (a) Deploy strategy results in 13.84% coverage (b) Rendezvous strategy results in 14.88% coverage.

Creating Cognitive Models and Markov Model

- Human choice of control actions displays learning and variability
- ACT-R models based on Instance-Based Learning learns from own experience and is not trained from human data
- Can be tailored to specific users (learning by imitation) or to a generic user (e.g., modulate parameters based on level of training or experience)
- Markov model trained from samples of cognitive model runs
- Models reproduce closely the trial-by-trial variations of human choice
- Models reproduce human sensitivity to relative quality of controls
- Cognitive model provides slightly closer fit to human performance





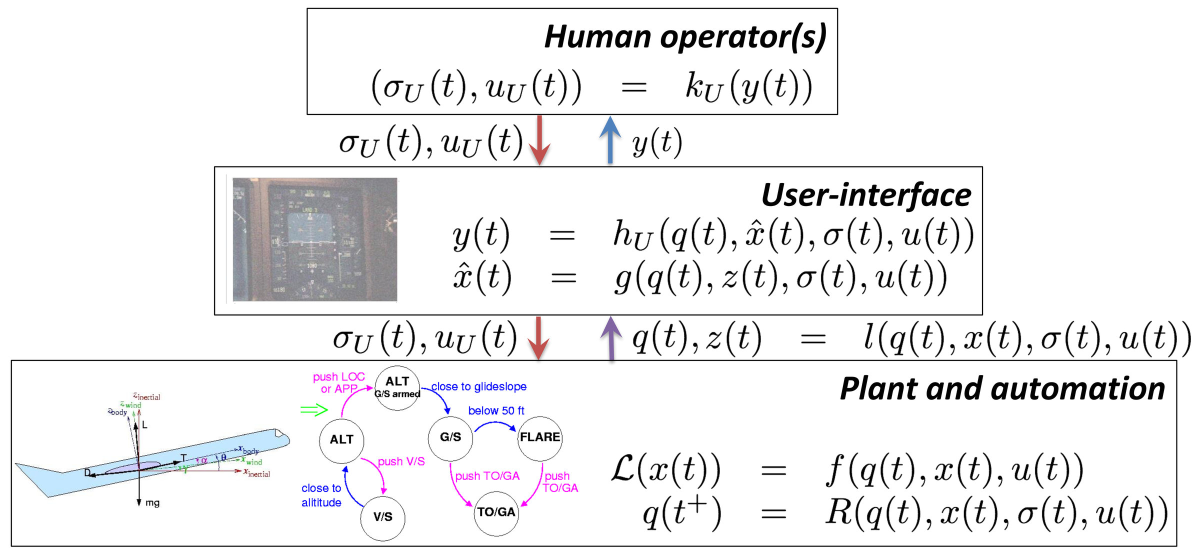
Performance of the three models in the test scenarios

Quantifying human interaction with CPS
- Mental workload management
- Level and intrusiveness of automation
- Effect of operator training

- Robotic hardware platform

Human-CPS Model

Method:
- Abstract user-interface is output map of a hybrid control system in which the state may be only partially known
- Human control actions map interface indications to control actions



Stochastic reachable sets under incomplete information

- Sufficient statistic in L^1 due to multiplicative cost function [3]

$$x_{n+1} = Ax_n + g(q_n, u_n, q_{n+1}) \qquad y_n^x = x_n + w_n$$

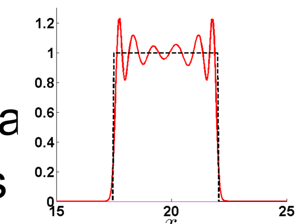
$$\eta_n(\rho, i_n) = \mathbb{E}^\pi \left[\mathbf{1}_q(q_n)\mathbf{1}_x(x_n) \prod_{i=0}^{n-1} \mathbf{1}_K(s_i) \middle| \rho, i_n \right]$$

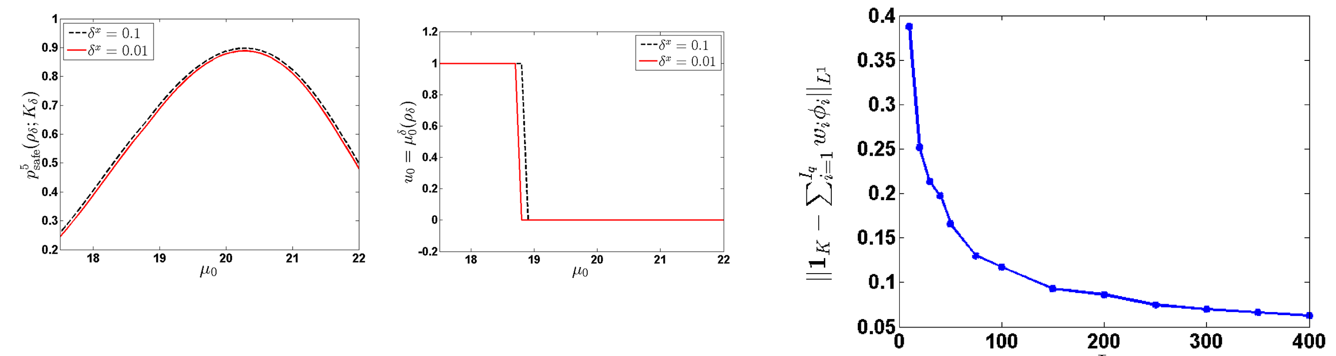
- Continuous-state, continuous-observation, continuous-input POMDP [1,3]
- Computational methods in point-based value iteration

$$V_n^*(\sigma) = \max_{u \in \mathcal{U}} \int_{\mathcal{Y}} \langle \alpha_{y,u,\sigma}, \sigma \rangle \, dy,$$

$$\alpha_{y,u,\sigma}(s) = \int_{\mathcal{S}} \alpha_{n+1}^{*(y)}(s') \tau_y(y|s', u) \tau_s(ds'|s, u) \mathbf{1}_K(s)$$

- Error bounds possible for approximation via a) discretization, and b) Gaussian mixtures





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