Provably Correct Shared Control for Human-Embedded Autonomous Systems

Ufuk Topcu — The University of Texas at Austin — *http://u-t-autonomous.info*

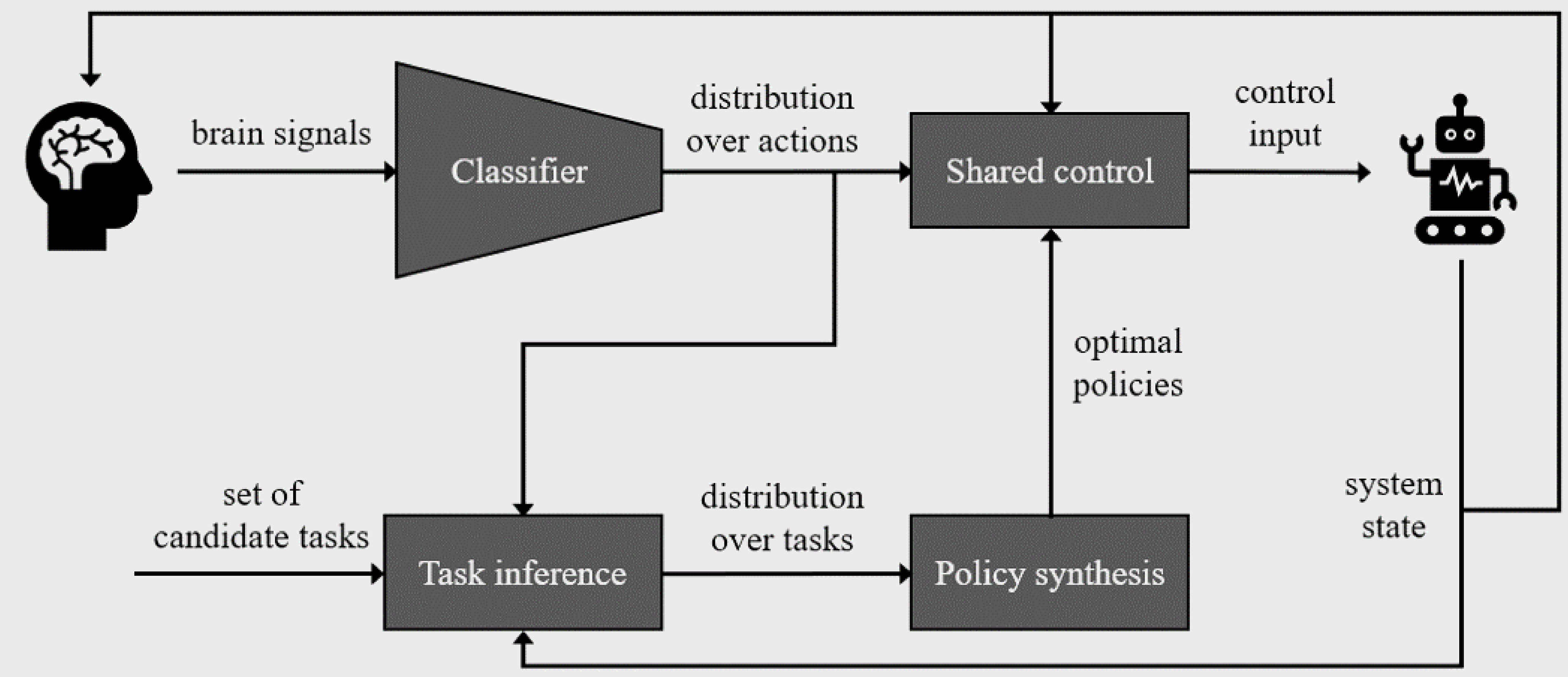
Human-embedded systems: Humans and autonomy are responsible for collective information acquisition, perception, cognition and decision-making at multiple and varying levels of abstraction.

Objective of the project: Develop languages, algorithms and demonstrations for the formal specification and automated synthesis of *shared control* protocols.

An enabling factor

Convergence between learning, formal methods, and control

formal methods
learning — control



Research thrusts

Specifications and modeling for shared control: What does it mean to be provably correct in human-embedded autonomous systems, and how can we represent correctness in formal specifications?

Automated synthesis of shared control protocols: How can we mathematically abstract shared control, and automatically synthesize shared control protocols from formal specifications?

Shared control through human-autonomy interfaces: How can we account for the limitations in expressivity, precision and bandwidth of human-autonomy interfaces, and co-design controllers and interfaces?

Shared Control for Temporal Logic Tasks in Brain-Machine-Interface Applications

An application in brain-machine interface:

A human trying to control a wheelchair through brain signals

How can we design a shared-control framework to augment human's capabilities?

Challenges:

- Human's unknown intent and preferences
- Imperfect interface and uncertain processing
- Online integration of data into sequential decision making

Problem statement:

Given

- A Markov decision process $\mathcal{M} = (\mathcal{S}, s_{init}, \mathcal{A}, \mathcal{T}, \mathcal{AP}, \mathcal{L})$
- A safety constraint φ_s along a safety level $\lambda_s \in [0,1]$
- A set of template tasks $\mathrm{T} = \{\tau_1, \tau_2, \dots, \tau_k\}$
- A classifier $C : X \to Y$ mapping the human brain signals to distribution over actions

The goal is to compute an online policy π_t^* optimizing

trade-off parameter

$$\max_{\pi_t} \overbrace{\Pr(\mathcal{M}_{s_0}^{\pi_t} \models \varphi^*)}^{\text{probability of task success}} + \alpha \overbrace{\sum_{t=0}^{T} \delta(\pi_t(s_t), y_t)}^{\text{divergence from human's intended behavior}}$$

$$\text{subject to} \quad \underbrace{\Pr(\mathcal{M}_{s_0}^{\pi_t} \models \varphi_s) \geq \lambda_s}_{\text{safety constraint}}$$

Proposed shared-control algorithm:

Blending a data-driven policy with a human rational policy

blending parameter

$$\overbrace{\pi_t^b(a_t = a | s_0, s_1, \dots, s_t)}^{\text{blended policy}} = \gamma_t \overbrace{\bar{\pi}_t^d(a_t = a | s_t)}^{\text{data-driven policy}}$$
$$+ (1 - \gamma_t) \sum_{\varphi \in \Phi} \underbrace{\Pr(\varphi = \varphi^*)}_{\text{belief over a tasks obtained through Bayesian inference}} \underbrace{\pi_t^r(a_t = a | s_0, s_1, \dots, s_t, \varphi = \varphi^*)}_{\text{rational policy based on the concept of Boltzmann rationality}}$$

set of candidate tasks instantiated from the template tasks

Effect of perturbing a policy through blending on the task success:

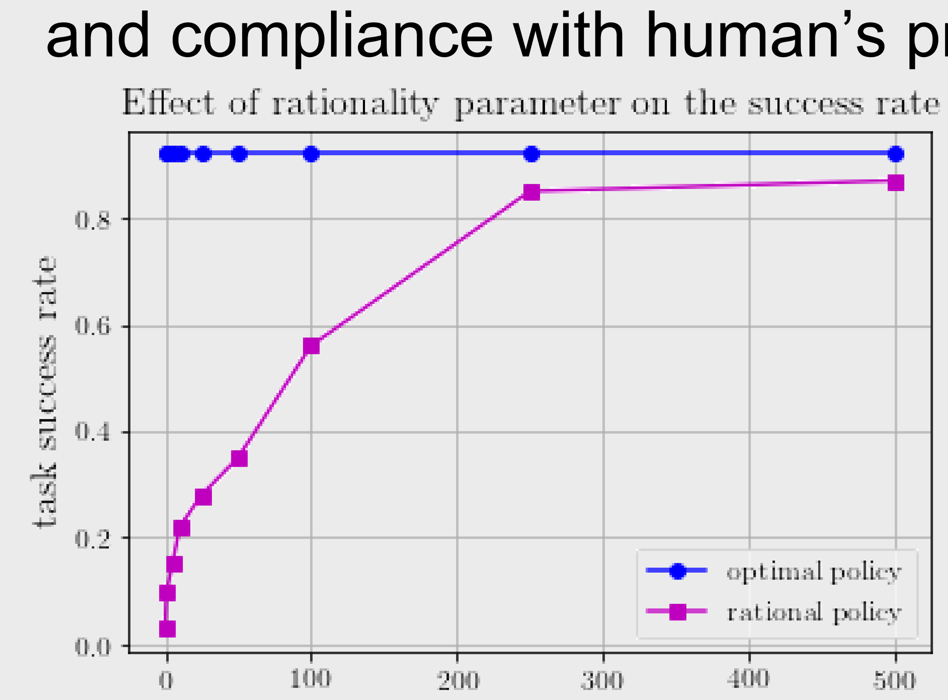
$$\left|\Pr(\mathcal{M}_{s_0}^{\pi} \models \varphi) - \Pr(\mathcal{M}_{s_0}^{\pi'} \models \varphi)\right| \leq (1 + \epsilon \underbrace{\delta/\eta}_{\text{properties of the system and policy}})^{2|\mathcal{S}|} - 1$$

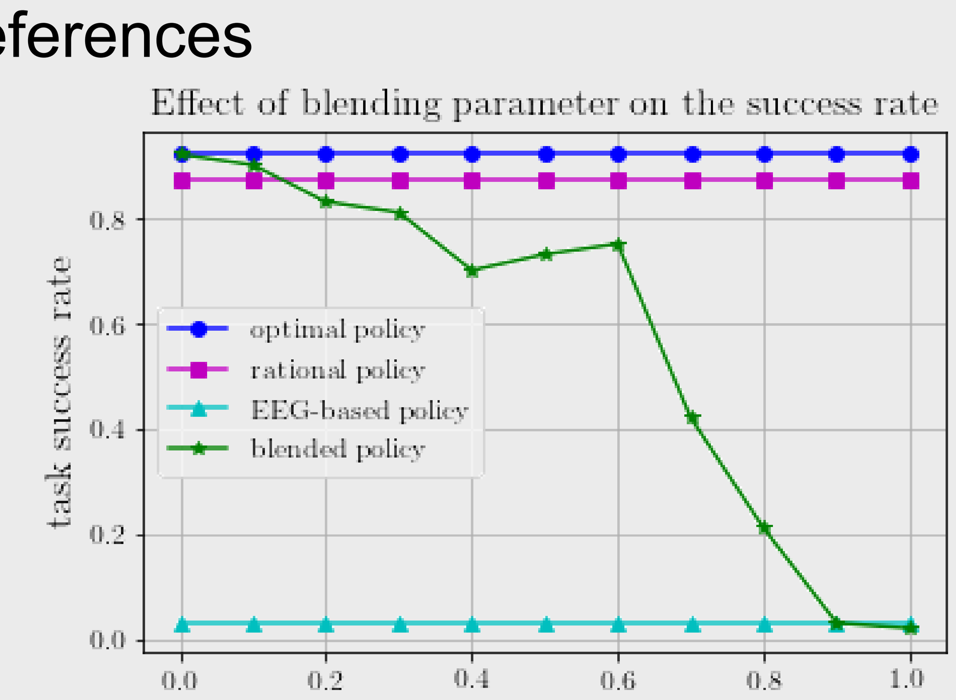
perturbation amount

Empirical results:

- Classifier's inaccuracy deteriorates the success rate and task completion time
- Lower rationality parameter results in higher suboptimality of the rational policy
- Blending parameter controls the trade-off between performance and compliance with human's preferences

Classifier's noise	Success rate	Completion time
[0.0,0.1]	0.90	27.58 s
[0.2,0.4]	0.77	42.16 s
[0.4,0.8]	0.57	78.11 s





Ongoing and future work:

- Incorporating error-related potential as another human feedback
- Analyzing the theoretical connection between the classifier's performance and shared control's performance
- Evaluating the algorithm through a human user study