Transfer Learning of Cyber-Physical Systems via Alternative Simulation Relations



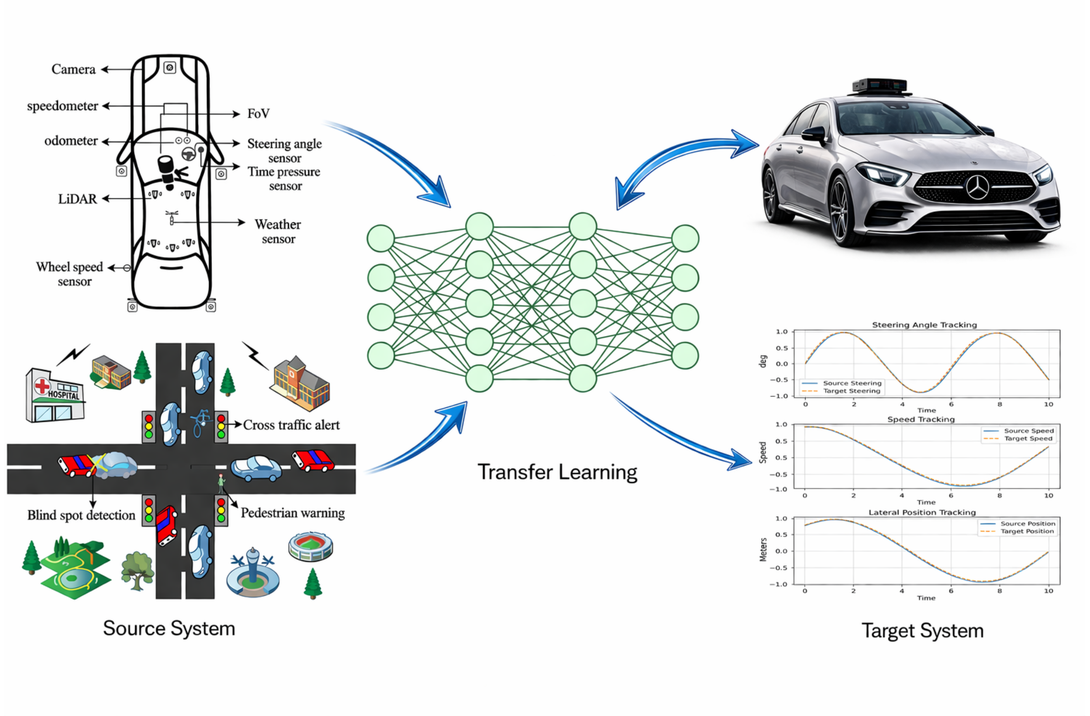
Reza Kazemi

reza.kazemi@sosy.ifi.lmu.de

Supervisors: Majid Zamani

Motivation

- Cyber-physical systems are **high-dimensional and complex**
- Examples: autonomous driving, robotics, smart infrastructure
- Direct controller design is:
  - Computationally expensive
  - Hard to verify
- Use a simpler **source (abstract) system**
- Transfer control via an **interface mapping**
- Reduce complexity while preserving guarantees
- Enables reuse of controllers across environments
- Key question: **Can we guarantee performance after transfer?**



Transfer learning in Self-Driving Cars

Transfer Learning and Alternative Simulation Relation

- Relates a **source system** to a **target system**
- Captures similarity via comparison function Q
- Ensures outputs remain **close over time**
- Enables **safe controller transfer**
- Provides formal guarantees for transfer learning

Problem Setup

$$x_1(k+1) = f_1(x_1(k), u_1(k)), \quad y_1(k) = h_1(x_1(k)), \quad (1)$$
$$x_2(k+1) = f_2(x_2(k), u_2(k)), \quad y_2(k) = h_2(x_2(k)), \quad (2)$$

- x_1: target system x_2: source system
- κ: interface mapping
- $Q(x_1, x_2)$: mismatch measure
- Goal: ensure $y_1 \approx y_2$

Assumption 1: Alternative Simulation Relation

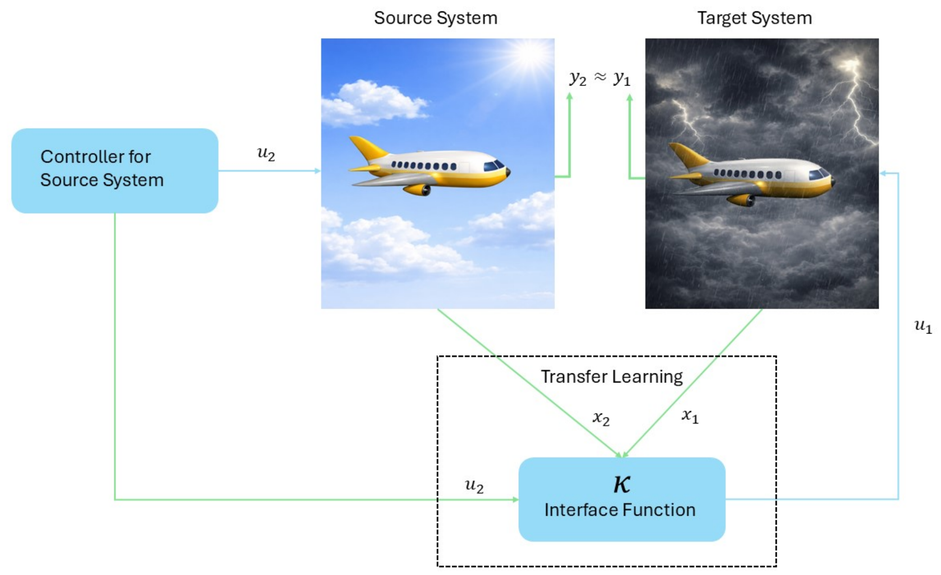
There exist constants $\gamma > 0$, $\rho \in (0, 1)$, $\delta \geq 0$ such that:

1. For all $x_2 \in X_2$ there exists $x_1 \in X_1$ with

$$\gamma \|h_1(x_1) - h_2(x_2)\|^2 \leq Q(x_1, x_2).$$

2. For all $(x_1, x_2) \in X_1 \times X_2$ and all $u_2 \in U_2$,

$$Q\big(f_1(x_1, \kappa(x_1, x_2, u_2)), f_2(x_2, u_2)\big) + (\rho - 1)\delta \leq \rho\, Q(x_1, x_2).$$



Controller transfer via interface κ ensuring similar outputs

Interpretation

- Source system is easier to control and analyze
- Interface κ adapts control inputs to the target system
- Function Q quantifies mismatch between trajectories
- Guarantees bounded output deviation over time

Key Contribution

- Abstraction-based guarantees
- Provides:
  - Output mismatch bounds
  - Stability guarantees
  - Scalable verification for complex systems
- Reduces complexity of controller design

Applications

- Autonomous driving under varying environments
- Robotics and multi-agent systems
- Smart infrastructure and industrial automation

References

[1] Amirreza Alavi, Alireza Nadali, Majid Zamani, and Saber Jafarpour. Neural barrier certificates for monotone systems. *IEEE Control Systems Letters*, 2025.

[2] Alireza Nadali, Bingzhuo Zhong, Ashutosh Trivedi, and Majid Zamani. Transfer learning for control systems via neural simulation relations. *arXiv preprint arXiv:2412.01783*, 2024.