Time-Centric Reactive Software
Workshop at Embedded Systems Week (ESWEEK) 2026 in Barcelona, Spain, on October 8-9, 2026

Timing Behavior Analysis for Time-Sensitive Distributed Human- and Agent-in-the-Loop Cyber-Physical Systems

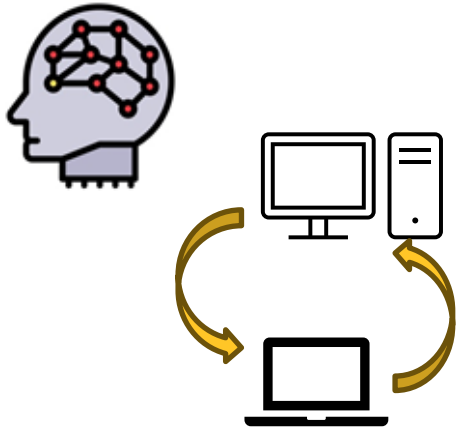
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GitHub: https://github.com/asu-kim/prototype-agentic-driving-coach

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Motivation for Understanding Sources of Latencies

- Predictable **timing behavior** is essential in Cyber-Physical Systems (CPS)
  - Central to the design of **resilient CPS**
- Human and agent-in-the-loop CPS has timing variability due to
  - AI reasoning
  - Human interaction
  - Sensing and actuation
  - Network communication





- Analyzing these latency sources is crucial for safety-critical CPS

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Goal & Approach for Analyzing Different Latency

- **Goal:** Analyze the timing behavior and account for latency sources in distributed human- and agent-in-the-loop CPS
  - Characterize sensing, communication, AI, and human latencies
  - Test the effects of timing variability
  - Monitor timing violations
- **Approach:** Deterministic model of computation

  "***Determinism****: given time-stamped inputs and initial state, there is only one possible output behavior* [1]"
- **Advantage:** Determinism enables **repeatable testing of experiments**
  - Isolate timing effects

[1] E. A. Lee, "Determinism," ACM Transactions on Embedded Computing Systems (TECS), vol. 20, no. 5, pp. 1–34, 2021.

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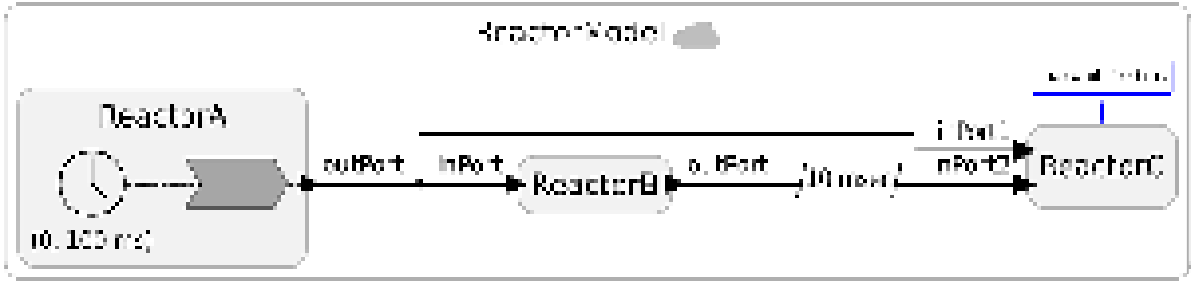
Technical Contributions of Our Work

1. Prototype for timing analysis of distributed human and agent-in-the-loop CPS: **Agentic Driving Coach**
2. Characterize latency across AI reasoning, driver monitoring, communication, visualization, and human-agent interaction
3. Lingua Franca based federated reactor MoC for our prototype: Agentic Driving Coach
4. Evaluate the impact of added delay on system timing behavior

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Background: Reactor MoC, Lingua Franca & Distributed Execution

- ***Reactor*** [2] model of computation (MoC) is a ***deterministic*** variant of actor [3] MoC
- Lingua Franca [4] (LF) is an open-source framework based on reactor MoC
- Lingua Franca provides deterministic scheduling, reaction ordering, timing constructs, tracing supports



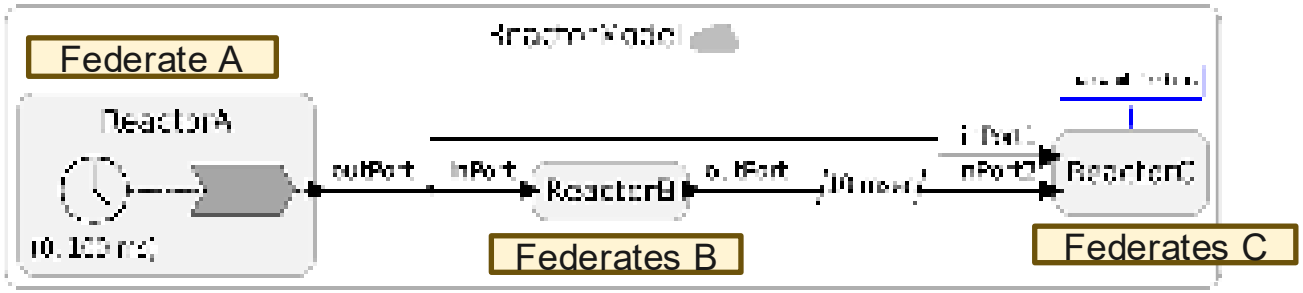
- LF has two timelines
  - Physical time - Wall clock time
  - Logical time - LF program-assigned timing of events

[2] M. Lohstroh et al., “Reactors: A deterministic model for composable reactive systems,” in Int'l Workshop on Design, Modeling, & Evaluation of CPS 2019
[3] C. Hewitt. 2010. Actor Model of Computation: Scalable Robust Information Systems. arXiv preprint arXiv:1008.1459
[4] M. Lohstroh et al. "Toward a lingua franca for deterministic concurrent systems." *ACM TECS* vol. 20, no. 4, 2021.

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Background: Federated Programs & Distributed Execution

- LF supports distributed executions using ***"federated programs"***
- ***Federates*** are top-level reactors executed
  - Same machine
  - Networked machine communicating over TCP/IP
- LF's provides ***maxwait*** construct which explained in the later slides



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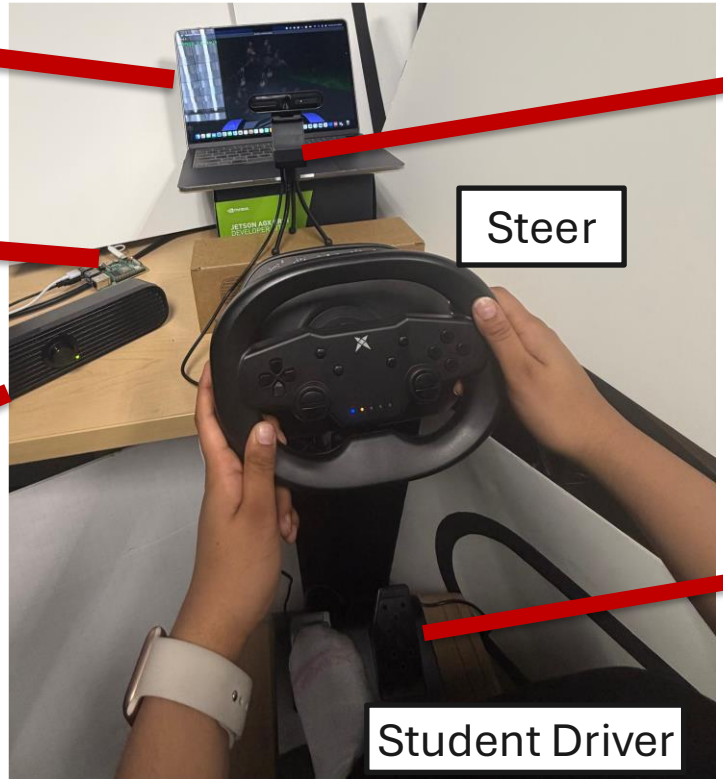
Prototype of Human and Agent-in-the-Loop CPS

Agentic Driving Coach

Environment Visualization Using MuJoCo

Raspberry Pi 4 Model B

Speaker for Agentic Coach Instruction Delivery

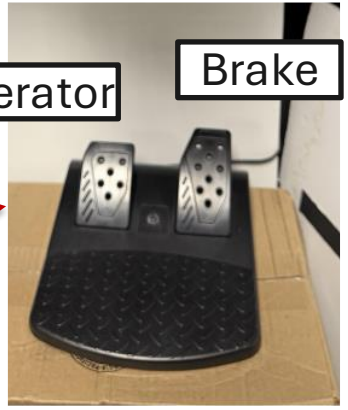




Video Input (Head, Eye)

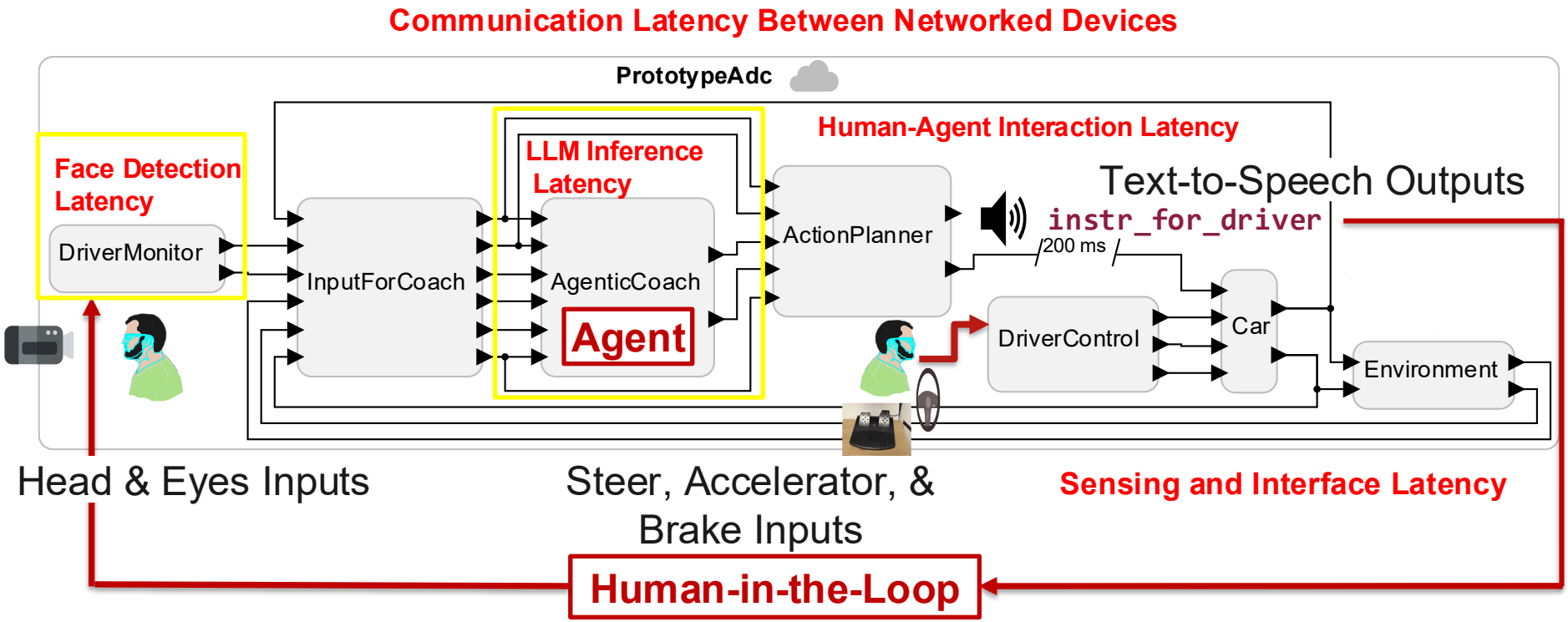
Accelerator

Brake



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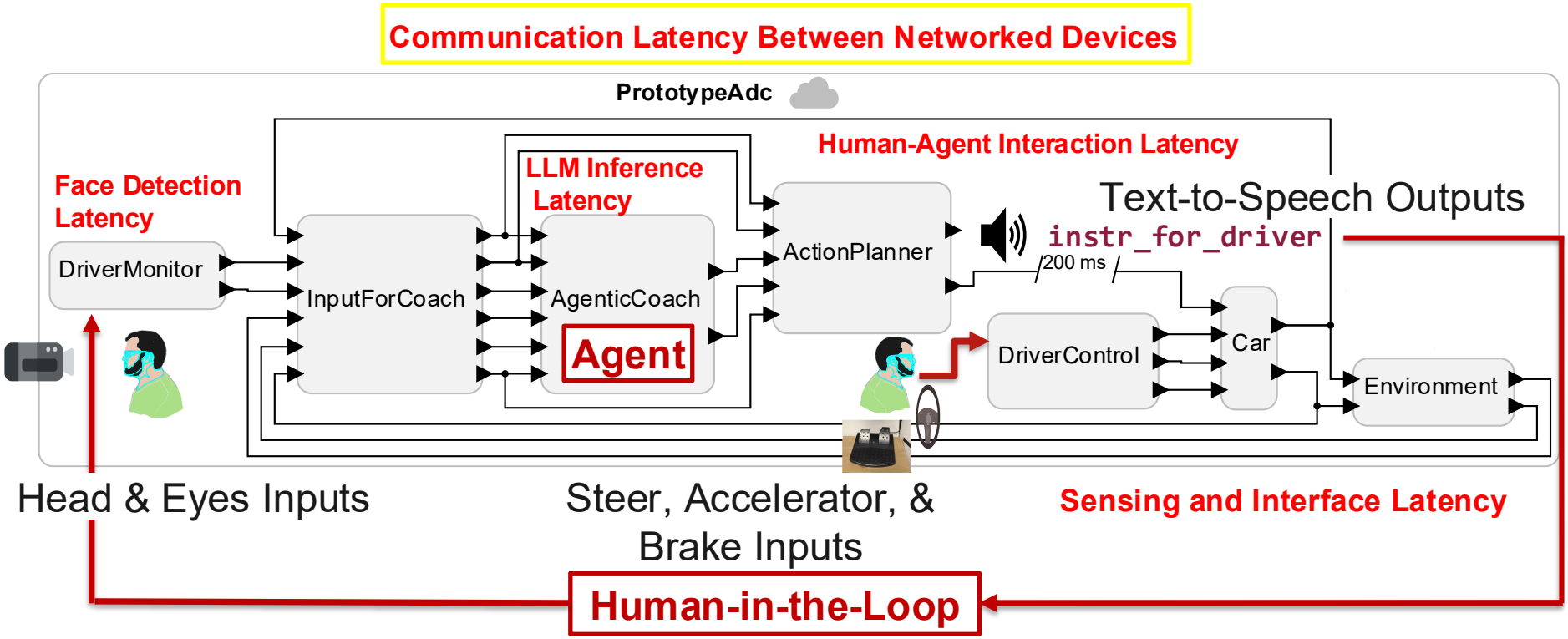
Latency Sources Analysis: AI/ML Reasoning



Empirical maximum and 95th percentile latency values are recorded over 300 runs

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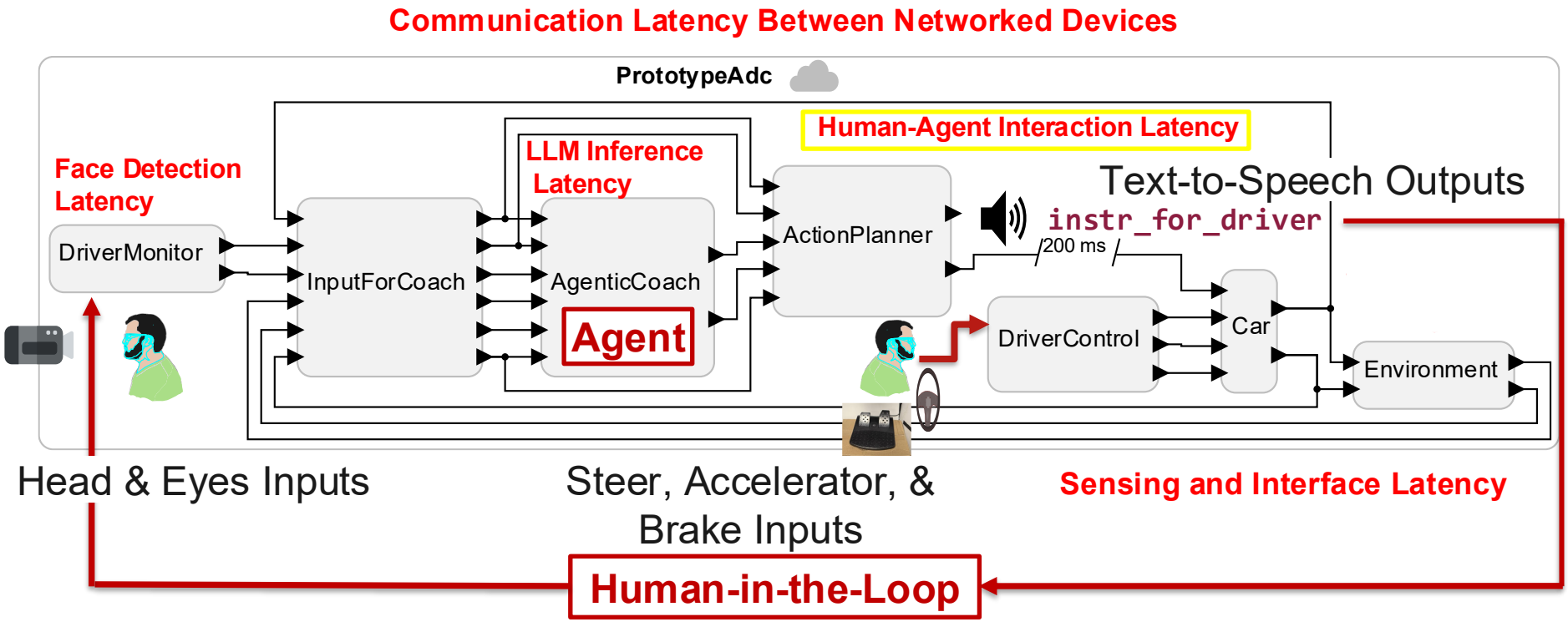
Latency Sources Analysis: Network Communication



Empirical maximum and 95th percentile latency values are recorded over 300 runs

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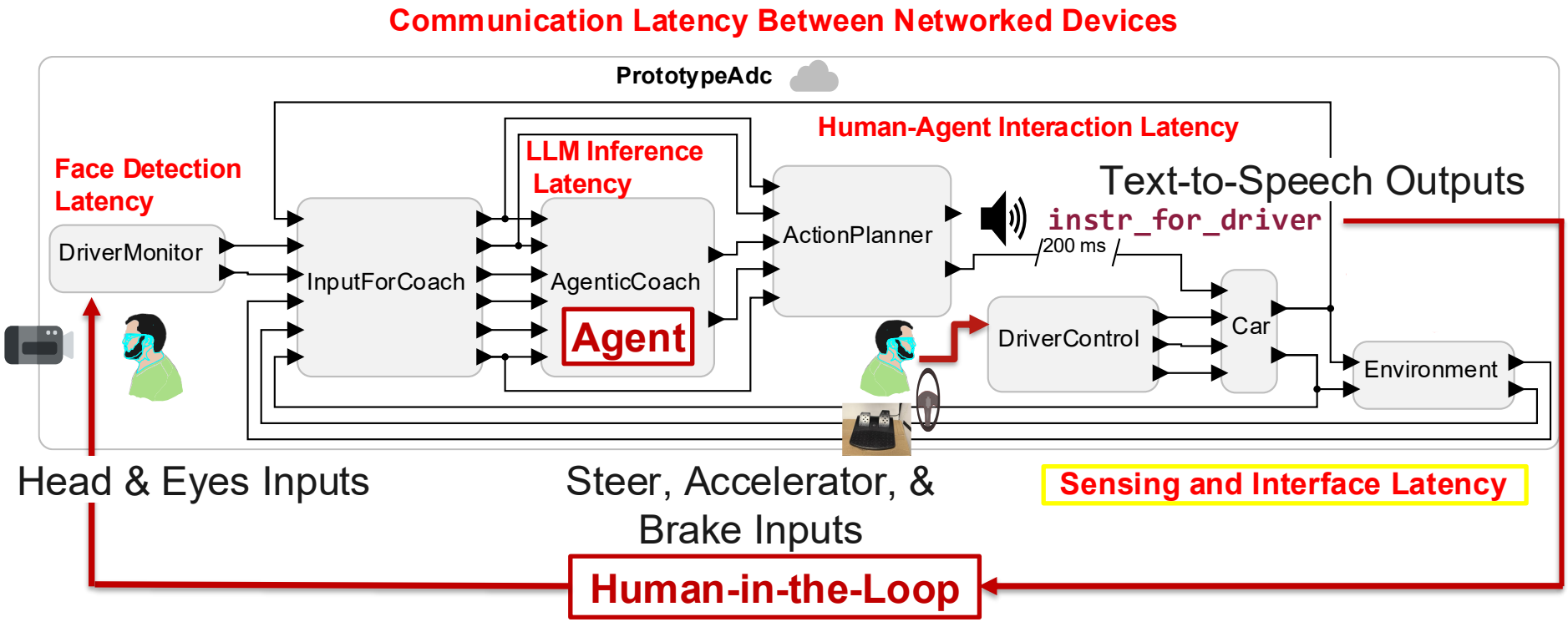
Latency Sources Analysis: Human-Agent Interaction



Empirical maximum and 95th percentile latency values are recorded over 300 runs

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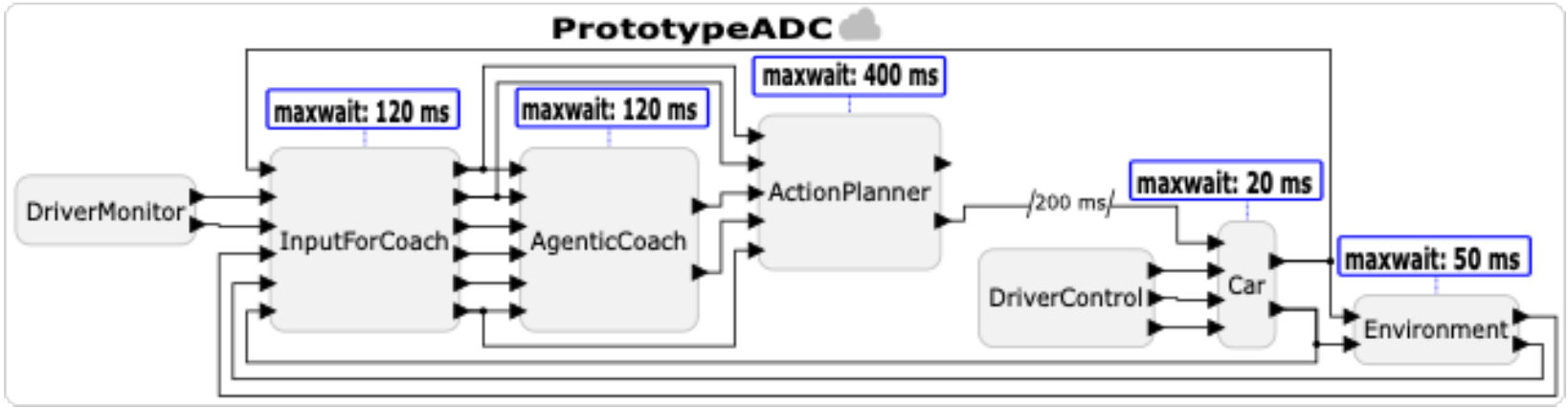
Latency Sources Analysis: Sensing, Interface and Initialization



Empirical maximum and 95th percentile latency values are recorded over 300 runs

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Configuring Timing Behavior Using LF's Timing Constructs



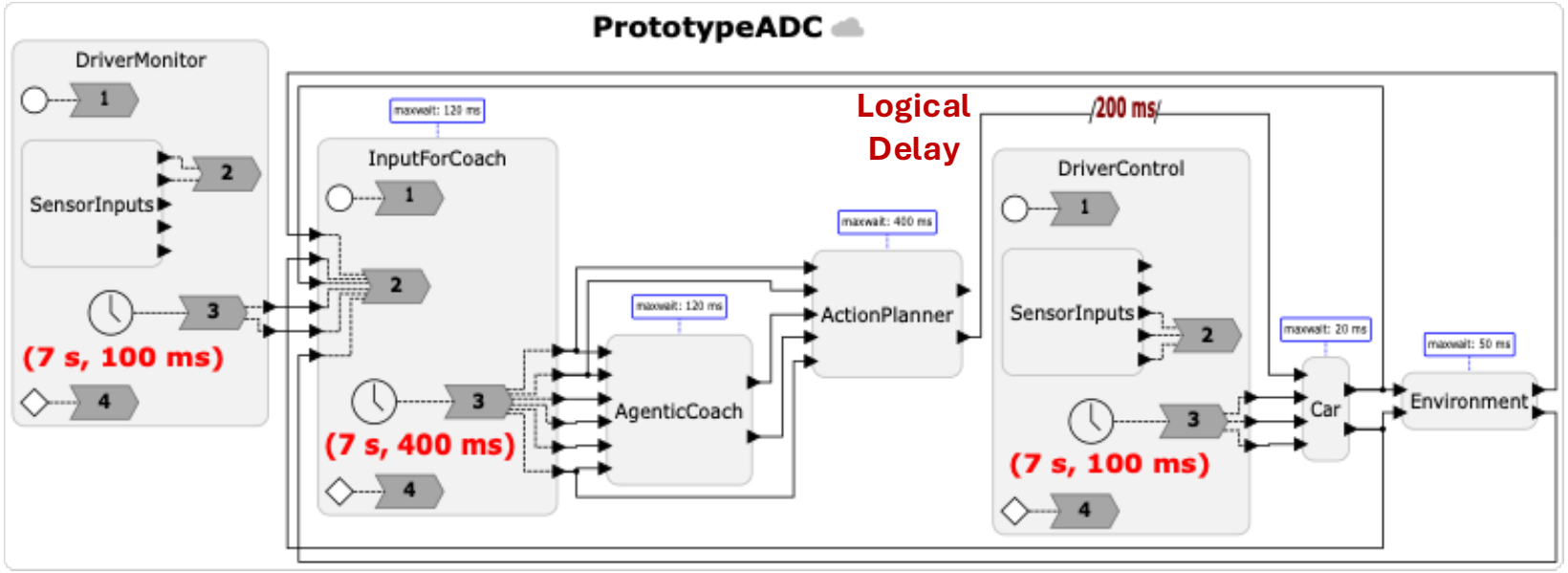
Federated Reactor Model

- **Maxwait [5]:** bounds the maximum time a federate waits for input messages before advancing to the next logical time
  - Messages arriving after the configured maxwait are treated as **tardy messages**
  - Tardy-handler executes **fallback** behavior

[5] F. Paladino et al., "Maxwait: A Generalized Mechanism for Distributed Time-Sensitive Systems," arXiv preprint arXiv:2601.21146, 2026.

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Configuring Timing Behavior Using LF's Timing Constructs



Federated Reactor Model

- **Periodic timers** to read driver-based inputs and produce outputs
- **Logical delay** for modeling the agentic coach instruction-to-actuation latency

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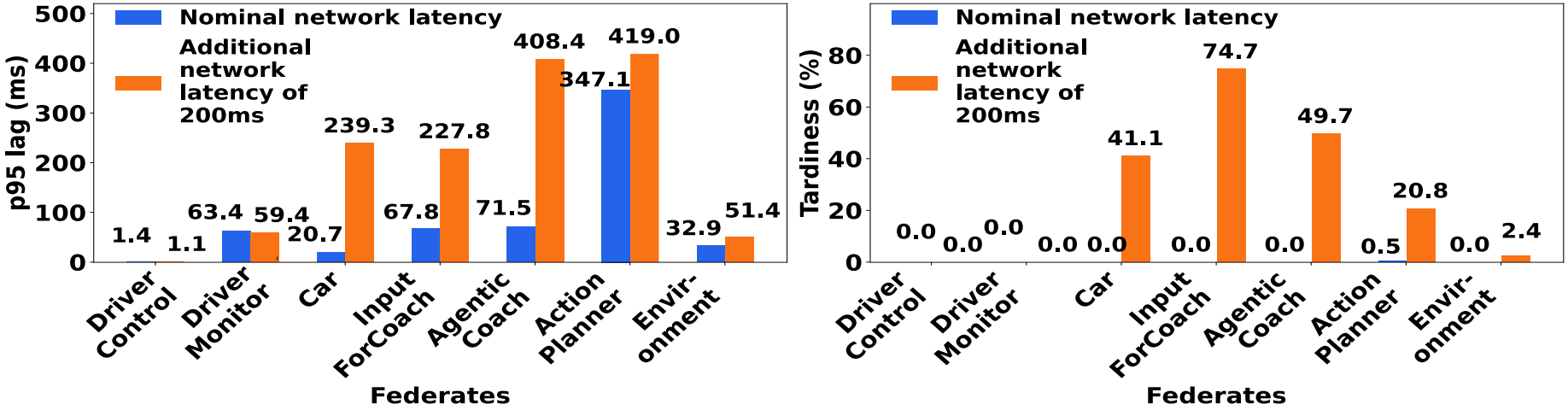
Evaluation Purpose and Metrics

- Evaluate the impact of communication delay and GPU contention on system timing
- Assess how maxwait bounds affect timing-assumption violations
- **Lag:** Delay between the physical time and the logical time at the beginning of the reaction
  - Physical time - Wall clock time
  - Logical time - LF program-assigned timing of events
- **Tardiness:** Percentage of reactions that invoke tardy handler to the total reaction invocation

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Impact of Added Communication Latency

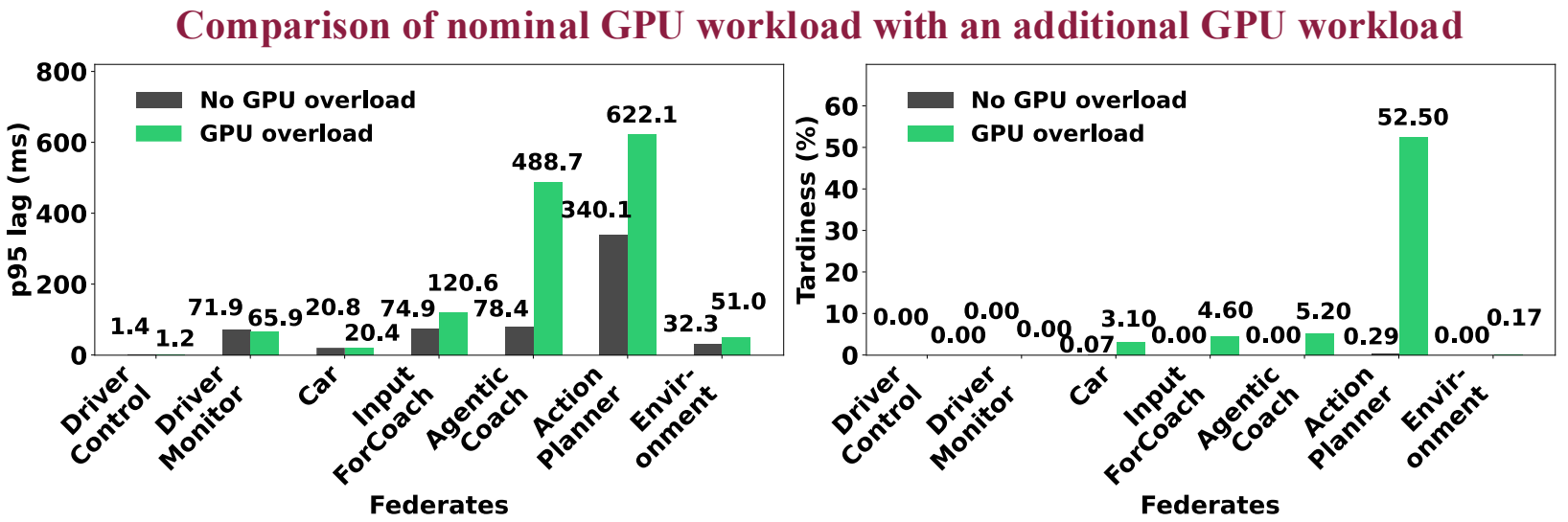
Comparison of nominal network execution with an additional 200ms communication delay



- Added communication delay increases lag, especially downstream in `Car`, `InputForCoach`, and `AgenticCoach`
- Tardiness also increases, showing that the configured maxwait assumptions are violated under higher network latency

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Impact of Added GPU Workload



- GPU contention increases LLM inference latency, producing higher lag in `AgenticCoach` and `ActionPlanner`
- `ActionPlanner` tardiness increases because `AgenticCoach` delivers its output later, demonstrating how compute latency propagates to downstream components

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Impact of Tighter Tardiness

Comparison of configured maxwait Vs tighter maxwait

Federate	Relaxed (20-400ms)		Tighter (10-170ms)	
	maxwait	Tardiness	*maxwait*	Tardiness
Car	20ms	0.0%	10ms	0.7%
Environment	50ms	0.0%	14ms	41.8%
InputForCoach	120ms	0.0%	111ms	0.0%
AgenticCoach	120ms	0.0%	111ms	0.0%
ActionPlanner	400ms	2.3%	170ms	23.4%

- We record and replay the same timestamped inputs, and vary only the configured maxwait values
- Tighter maxwait values results in a higher tardiness, showing time bound violation

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Summary of Evaluation Results

- If maxwait is set tight or there are additional delay, we have higher tardiness
- Higher tardiness implies that the configured maxwait assumption are violated
- **Note:** Lower tardiness does not guarantee better application performance!

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Demo Video

Lingua Franca:

An Open-Source Coordination Language for Deterministic Integration of Cyber-Physical Systems

lf-lang.org



Agentic-AI powered human-in-the-loop
CPS: Agentic Driving Coach

Demo Video

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Conclusion

- Presented a prototype for timing behavior analysis for human and agent in the loop CPS
- Characterized various latency sources
- Configured timing in the federated reactor MoC using maxwait, logical delays, timers, and startup offsets

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GitHub:
https://github.com/asu-kim/prototype-agentic-driving-coach

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