Residual Hybrid Motor Controller with Multi-Phase Learning

Johann Wiens, Christoph Reich
Institute for Data Science, Cloud Computing and IT-Security
Furtwangen University of Applied Sciences
Furtwangen, Germany
johann-wiens@outlook.com, christoph.reich@hs-furtwangen.de

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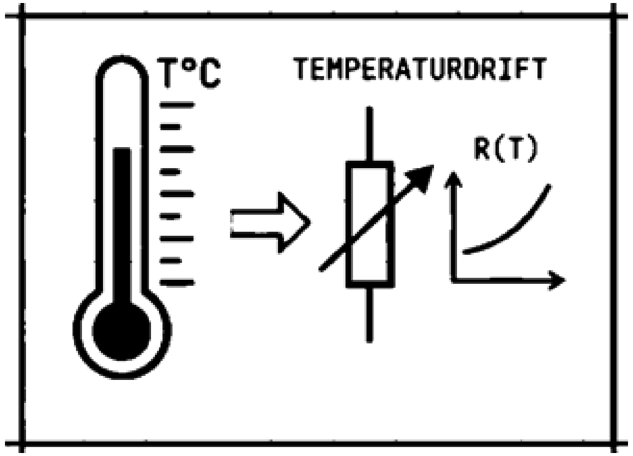
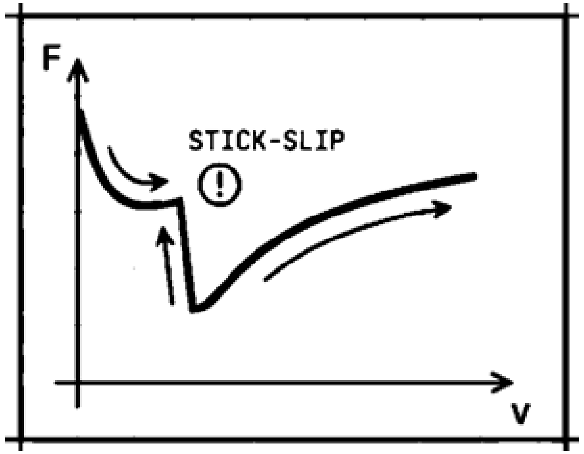
The Challenge in Modern Drive Technology

While PID controllers are the industry standard for stability, they reach their physical limits in compact drives. The control often requires a compromise between precision, overshoot and load on the actuator.

Examples

- Non-linearities
- Dynamic losses
- Drift
- Saturation





The Concept: Residual Hybrid Control

A hybrid approach that guarantees safety and learns precision. The proven PID controller remains the basis; the LSTM only corrects the residual error.

$$V_{tot}(k) = V_{PID}(k) + V_{LSTM}(k)$$

Basis – Safety

The PID controller is fixed (tuned) and guarantees basic stability.

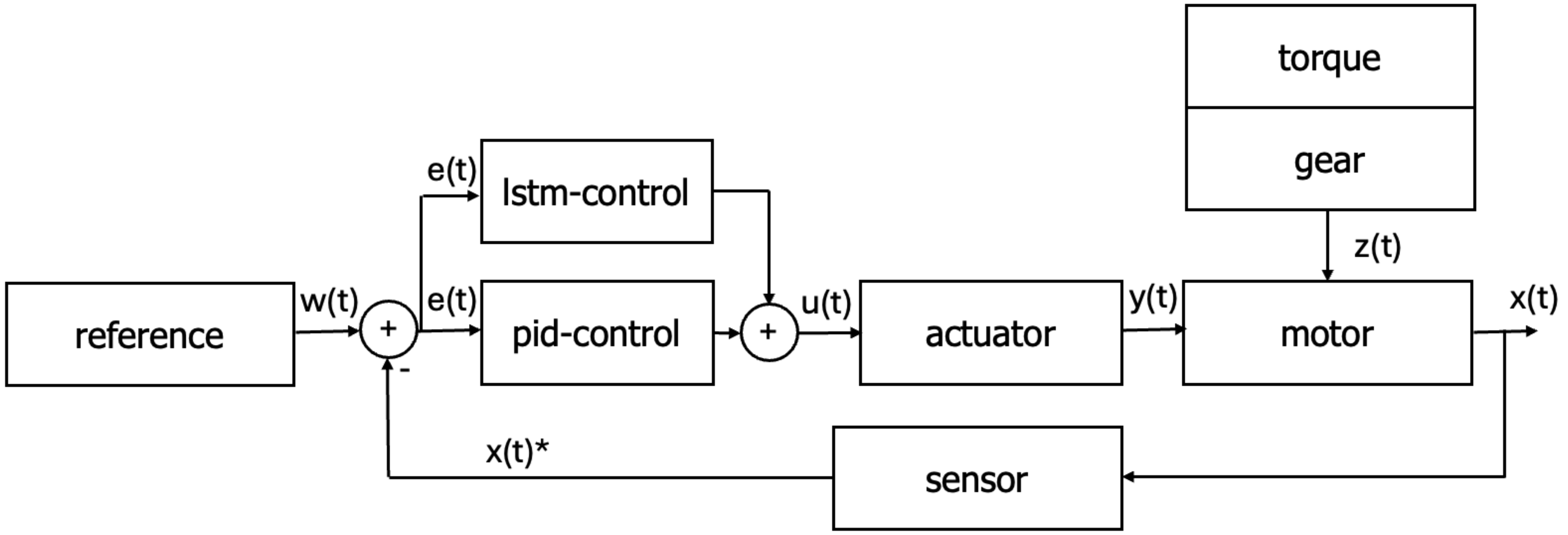
Residual correction

The LSTM acts (in parallel) to compensate for non-linear effects additively.

Hard limits

The output of the LSTM is strictly limited so that the PID retains the main authority....

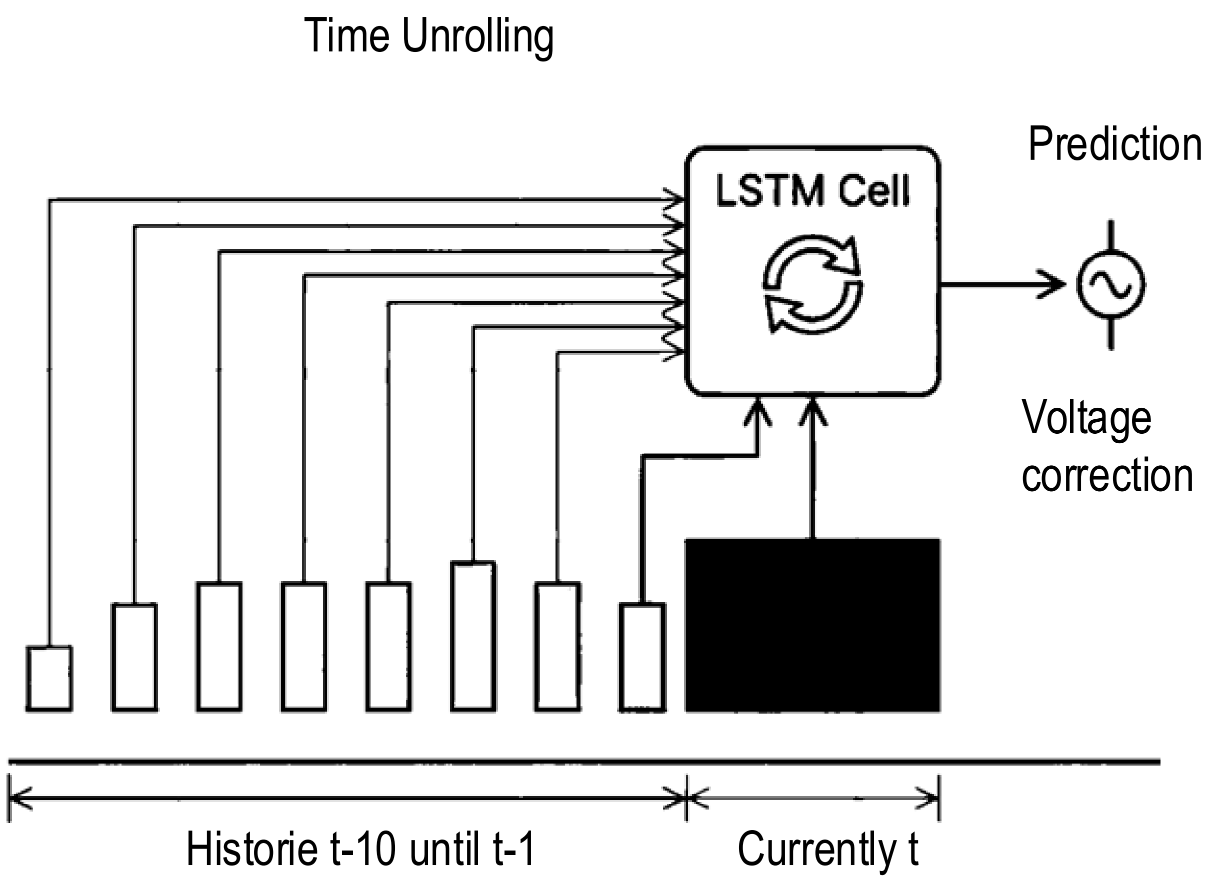
System Architecture and Signal Flow



Modelling Memory with LSTM

Friction and magnetic hysteresis depend not only on the current state, but also on the history.

- Type: 3-layer LSTM, hidden size 12
- Input: Last 10 time steps
- Function: Predictive compensation of recurring disturbance patterns



Learning Phase 1: Behavior Cloning (BC)

Objective:

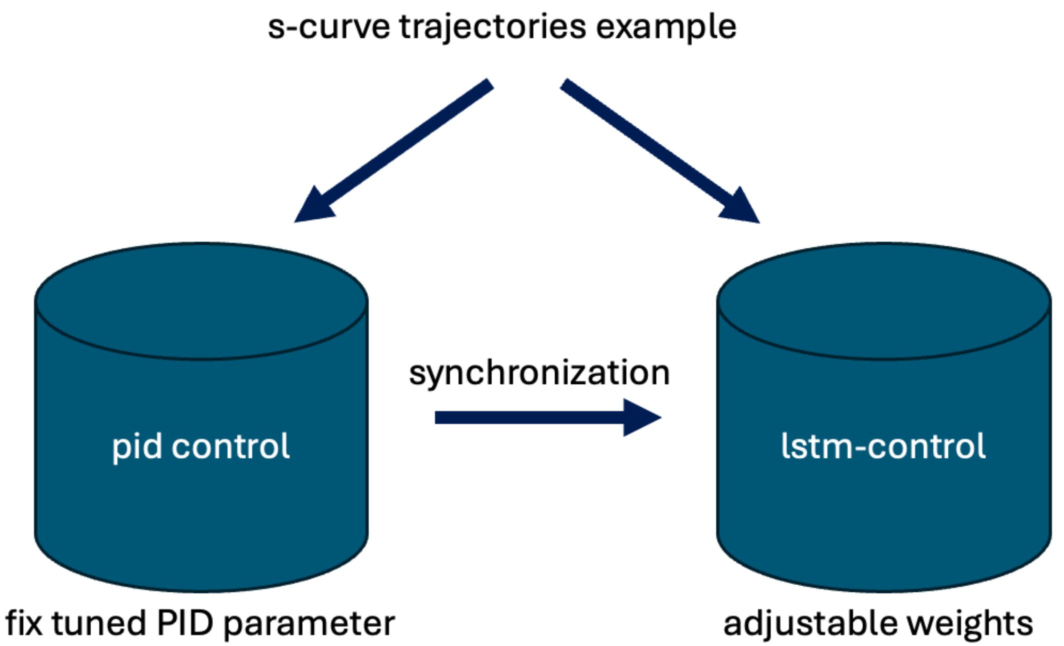
Creation of a secure starting point through imitation.

Process:

The LSTM is trained to imitate the output of the PID controller.

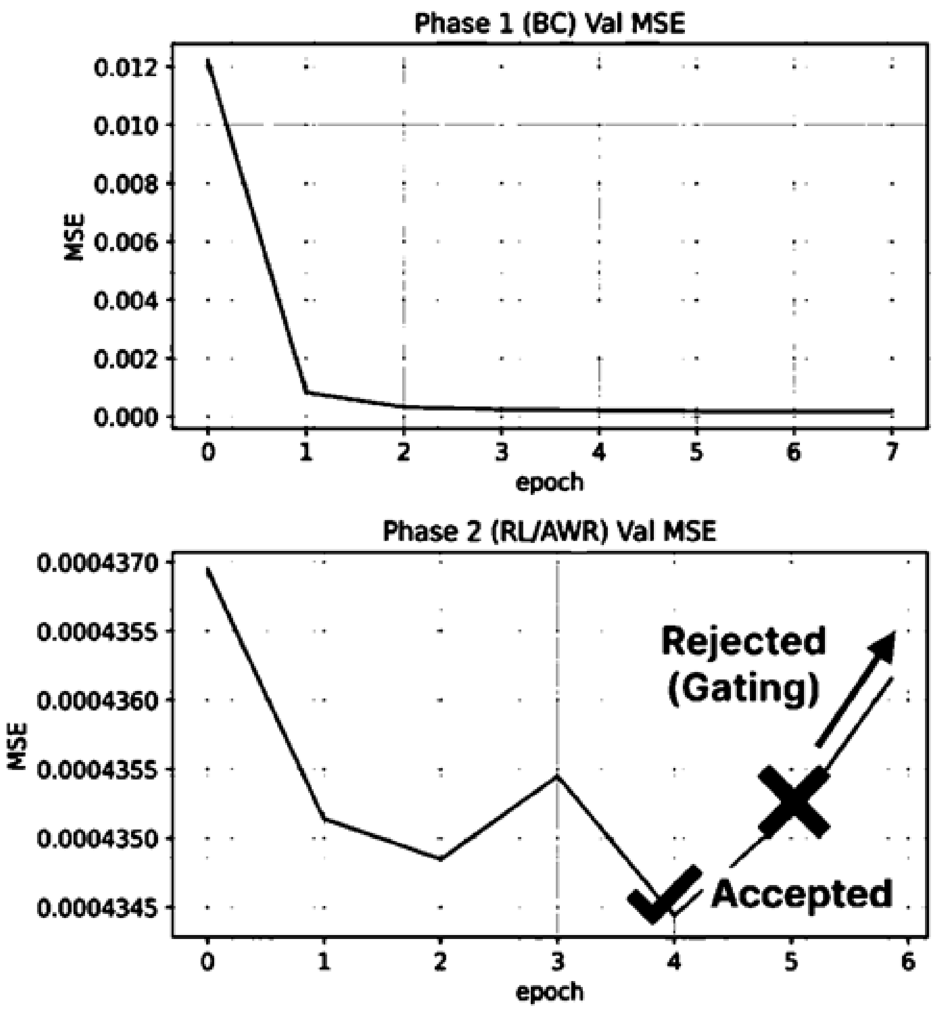
Result:

Avoidance of "random exploration". The agent starts stably.



Learning Phase 2: Advantage-Weighted Regression (AWR)

Optimisation through conservative reinforcement learning



Reinforcement learning:

Closed-loop interaction.

Advantage function:

Only rewards when error |e_hyb| ‹ |e_PID|.

Conservative gating:

Updates are only applied if validation improves.

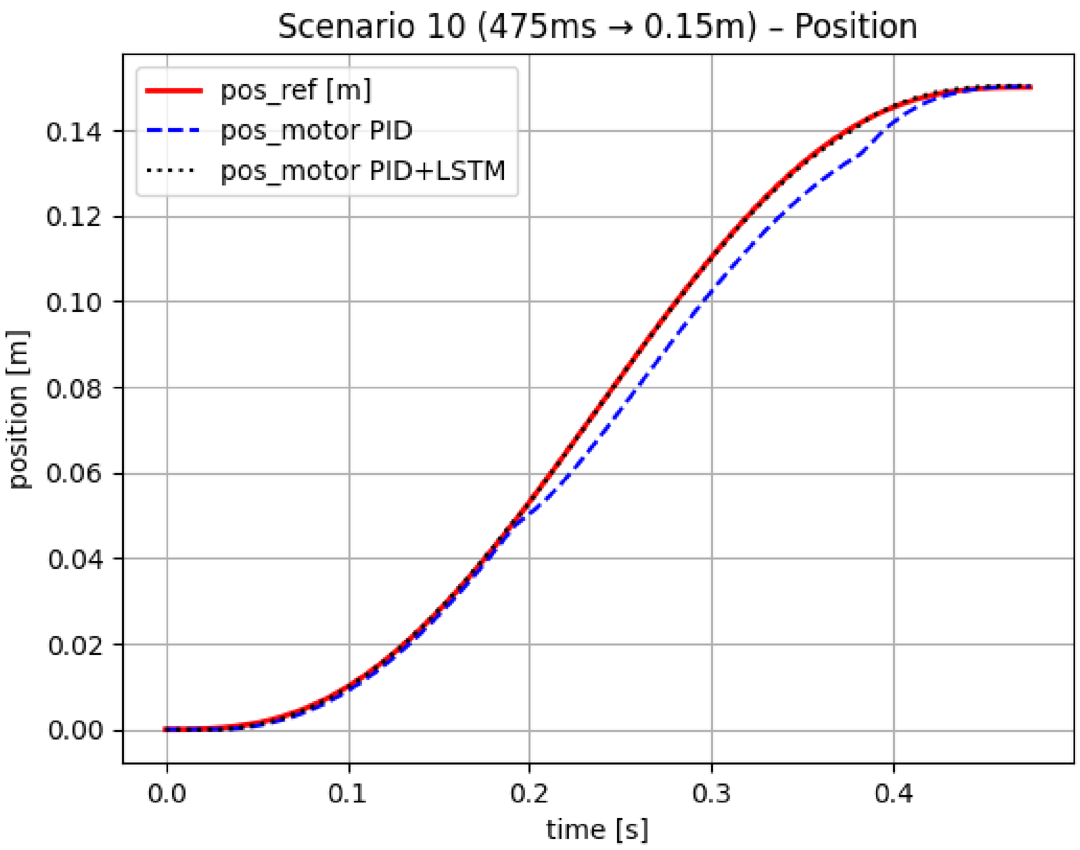
Validation Environment: The Digital Twin

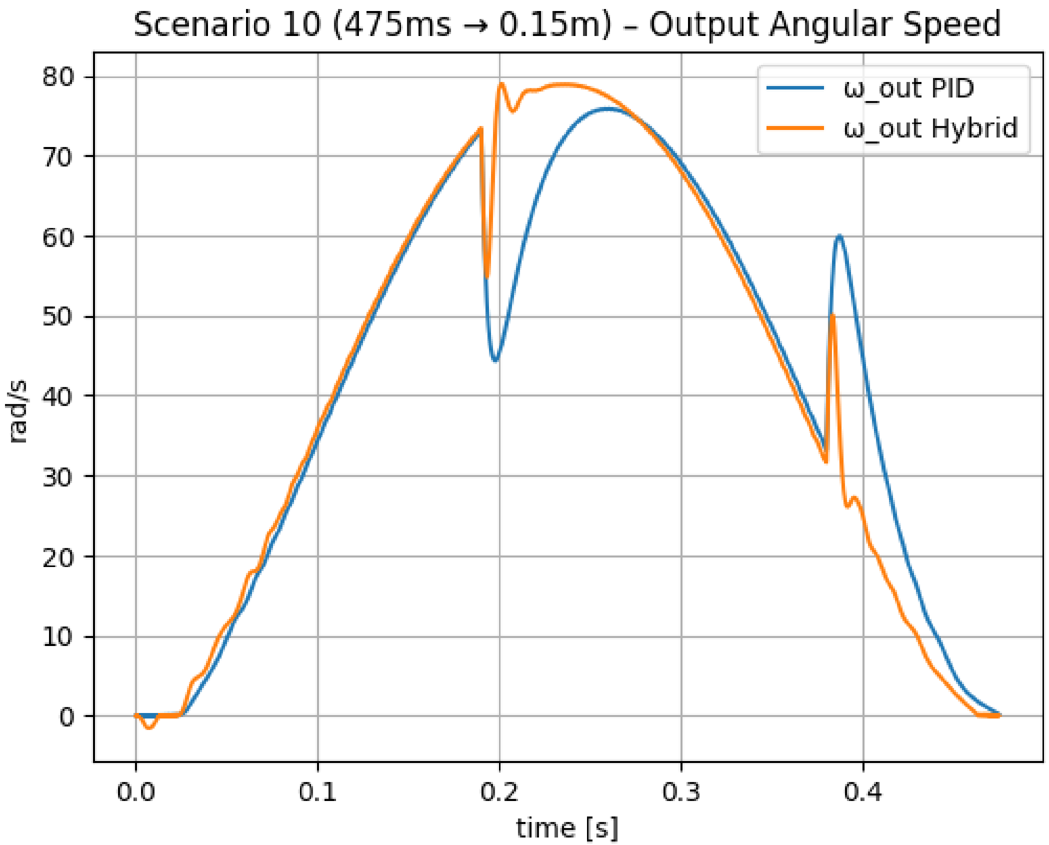
BLDC-Motor-model

Voltage, Load Torque →  → Position, Temperature

- Friction
- Iron losses
- Cogging torque
- PWM artifacts
- Saturations
- Thermal model

Results: Precise Trajectory Tracking

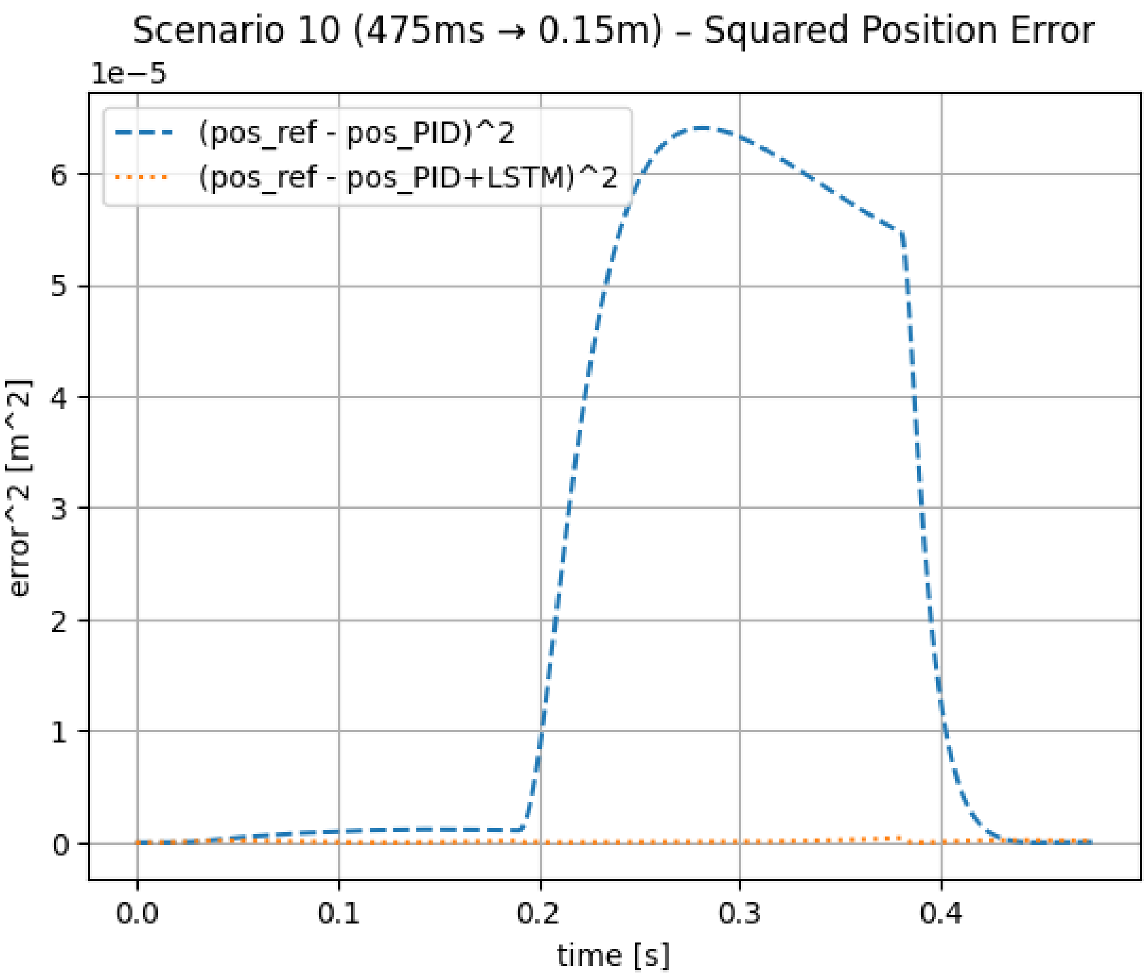




Quantitative Analysis: 98.5% Error Reduction

Reduction:

-98.5% Square root of the mean squared error (MSE)



Conclusion: High-performance Control with Guaranteed Safety

Architecture: Residual approach preserves PID stability and interpretability. AI as an add-on, not a black box.

Training: 2-phase learning (imitation -> AWR) prevents instability. Conservative gating ensures progress.

Performance: 98.5% error reduction in simulation. Smooth trajectories without overshoot.

Outlook: Validation on physical hardware (hardware-in-the-loop) using established safety limits.

Sources and References

Paper:

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Autoren:

Johann Wiens (johann-wiens@outlook.com)

Christoph Reich (christoph.reich@hs-furtwangen.de)

Institution:

Institute of Data Science, Cloud Computing and IT-Security Furtwangen University of Applied Sciences

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