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Sim-to-Real Reinforcement Learning for Hybrid Robotic System: Platform Design and Enhanced Hindsight Experience Replay

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This presentation explored recent advances in reinforcement learning for robotic operations, with a particular focus on overcoming the persistent challenges of sample inefficiency, sparse rewards, and the sim-to-real transfer gap. The speaker emphasized the growing value of RL in robotics, noting its capability to solve continuous-control problems, adapt to dynamic environments, and coordinate multi-joint systems. However, current progress is still constrained by the scarcity of transferable robotic platforms and the difficulty of achieving convergence when reward signals are sparse.

The talk first reviewed foundational RL algorithms commonly used in robotics, such as DDPG and PPO, which can address complex tasks like multi-joint coordination or force control. Several optimization strategies were discussed, including the integration of expert demonstrations, reward shaping, and curriculum learning, all aimed at stabilizing training and improving sample efficiency.

A central focus of the presentation was the evolution of Hindsight Experience Replay (HER), a powerful technique for mitigating sparse rewards. The speaker outlined its main variants: Curriculum-guided HER (CHER), which structures target relabeling by distance and diversity; Relay HER (RHER), which decomposes complex tasks into subtasks optimized progressively; and Model-based HER (MHER), which generates virtual targets using learned dynamics models. Despite these advances, HER still faces limitations in convergence and generalization, particularly when applied to hybrid robotic structures.

To address these gaps, the research introduces a novel hybrid robotic platform designed for high-precision and large-workspace tasks. The system integrates a three-axis linear stage with the OpenManipulator robotic arm, yielding a seven-degree-of-freedom configuration capable of coarse-to-fine motion. A high-fidelity simulation model and unified ROS-based communication framework allow seamless migration between simulation and physical execution, reducing the sim-to-real discrepancy that often undermines RL deployment.

On the algorithmic side, the proposed Enhanced HER (EHER) framework incorporates two key innovations. The first is Dual-Granularity Decomposition (DGD), a task-level strategy that divides global goals into coarse and fine targets aligned with the hybrid system’s physical structure, thereby simplifying learning. The second is Expert Experience Replay (EER), which selectively retains high-quality trajectories, integrates them with HER, and substantially improves training stability and convergence performance.

The presentation concluded by outlining future research directions, including the application of EHER to real-world tasks involving uncertainty, deformable objects, and multi-step assembly, with the aim of pushing RL-enabled robots toward greater autonomy and reliability in complex environments.