Title	軌道走行型パトロールロボットシステムの速度制御とSim-to-Real展開のための説明可能な深層強化学習フレームワーク
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Abstract

Intelligent facility monitoring increasingly relies on autonomous robotic systems, yet the deployment of learning-based control policies in real environments remains challenging due to their black-box nature and the discrepancy between simulation and real-world conditions. Rail-guided patrol robots, while mechanically stable and suitable for large indoor facilities, commonly operate with fixed-speed or rule-based controllers that do not adapt to variations in visual scene complexity. This dissertation presents a deep reinforcement learning–based framework for adaptive patrol speed control of a rail-guided robot system. Patrol speed control is formulated as a continuous decision-making problem in which the robot observes forward-facing RGB images and outputs a continuous velocity command. The Deep Deterministic Policy Gradient (DDPG) algorithm is employed to learn context-dependent speed modulation along a predefined rail trajectory. To encourage adaptation to visual conditions, an entropy-driven reward function is adopted. Image entropy is used as a proxy for visual information density, allowing the learned policy to adjust patrol speed in response to changes in visual scene complexity without relying on manually designed heuristics. This formulation enables perception-driven patrol behavior to emerge from visual statistics. To facilitate analysis of the learned policy, gradient-based visual interpretation is incorporated into the framework. Grad-CAM is applied to the actor network to generate action-specific attention maps that highlight image regions associated with speed decisions. These visualizations provide interpretable evidence of how visual inputs are reflected in control outputs and support qualitative inspection of internal policy behavior. For deployment, the visual discrepancy between simulation and real environments is addressed using CycleGAN-based unpaired image-to-image translation. Real camera images are translated into simulation-style representations, enabling zero-shot execution of the trained policy. The consistency of visual attention patterns before and after translation is examined through Grad-CAM-based analysis. Beyond algorithmic development, a complete rail-guided patrol robot system is implemented and deployed in an agricultural wholesale market on a ceiling-mounted rail loop of approximately 220 meters to verify system-level integration and operational feasibility. Experiments conducted in simulation and controlled testbeds involve the quantitative analysis of patrol behavior and visual attention patterns, and are used to examine behavioral consistency across environments, rather than to provide full validation of real-world performance.

This dissertation contributes to deep reinforcement learning and robotic perception by addressing adaptive patrol speed control under visually heterogeneous environments with a particular focus on policy interpretability. While prior work on learning-based control primarily emphasizes performance, it often provides limited insight into how perceptual information influences continuous control decisions. This research instead emphasizes interpretability as a means of analyzing and understanding learned behavior. A central contribution of this work is the formulation of patrol speed control as a perception-driven continuous control problem, in which visual scene complexity directly influences the learned policy. Image entropy is employed as a reward signal to reflect variations in visual information density, providing a practical mechanism for linking perception and control without relying on task-specific heuristics. Another key contribution is the application of Grad-CAM to the actor network of a continuous-action deep reinforcement learning policy. By producing action-specific attention maps, the proposed framework provides interpretable visual evidence of image regions associated with speed decisions. These visualizations are treated as correlational indicators rather than causal explanations, and their limitations are explicitly acknowledged. The integration of interpretability with sim-to-real transfer further strengthens the contribution of this research. Instead of evaluating domain adaptation solely through control performance, this dissertation examines whether interpretable visual cues remain consistent after visual domain translation. The analysis of Grad-CAM attention before and after CycleGAN-based translation provides empirical insight into the stability of interpretability across simulated and real environments. Overall, this dissertation does not claim the introduction of new learning algorithms or theoretical models. Its contribution lies in the structured integration of adaptive deep reinforcement learning, visual interpretability, and sim-to-real deployment within a unified patrol framework, offering methodological insights applicable to a broad range of robotic monitoring and inspection systems.

Keywords: Rail-guided patrol robot, Adaptive speed control, Deep reinforcement learning (DRL), DDPG-based robot control, Simulation-to-real transfer, CycleGAN-based domain adaptation, Explainable artificial intelligence (XAI), Grad-CAM visualization, Facility monitoring automation