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Development of ADS-based Operator Action Support System for Abnormal Operation

Hee-Jae Lee, Jonghyun Kim
Korea Advanced Institute of Science and Technology, 291 Daehak-ro, Yuseong-gu, Daejeon 34141, Republic of Korea
E-mail: jonghyun.kim@kaist.ac.kr

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1. Introduction

The safety of nuclear power plants (NPPs) must be ensured during their operation. In the event of unexpected transients or abnormal conditions, operators must take swift and appropriate actions to maintain the integrity of the reactor and containment. To support these tasks, abnormal operating procedures (AOPs) are equipped in NPPs. However, as NPP systems are complex, procedures along can struggle to cover all possible abnormal scenarios. When procedural gaps occur, operators transition into knowledge-based behavior, relying on their experience and intuition. In such high-pressure situations, the surge in decision-making demand and the dispersion of monitoring variables can lead to human errors [1-4].

To address this, this study aims to develop an operator action support system that provides operators with optimal action and its underlying rationales in real-time. To achieve this, first, this study incorporates abstraction decomposition space (ADS) into designing deep reinforcement learning (DRL) algorithm. By incorporating the functional hierarchy (from physical components to system goals) into the reward function, the DRL agent learns to perceive the plant's state through the lens of hierarchical functional structure. Second, this study develops a GUI interface to visualize ADS-based action paths. It visualizes how a specific action restores an abstract function within the ADS hierarchy and the causal sequence to achieve ultimate system goals.

2. Work Domain Analysis using ADS

NPPs are complex socio-technical systems with numerous interconnected components. As such, physical connectivity alone is insufficient for identifying the root causes and propagation effects of incidents/accidents. To address this, this study utilizes ADS, a fundamental tool of cognitive systems engineering [5].

The hierarchical structure of ADS enables the vertical tracking of anomalies from physical elements to system functions. ADS models a system through five levels: 1) functional purpose, 2) abstraction function, 3) generalized function, and 4) physical function. Fig. 1 illustrates the ADS diagram developed for the target system. For this study, the Westinghouse 900MWe (WH-900), a three-loop pressurized water reactor, was selected as the reference plant.

Fig. 1 illustrates the ADS diagram developed for the target system. The ADS developed in this study is centered on a system functional purpose: 'Maintaining RCS Inventory'. To achieve this goal, the system is decomposed into two primary abstraction functions: 'Pressurizer (PZR) level' and 'Volume Control Tank (VCT) level'.

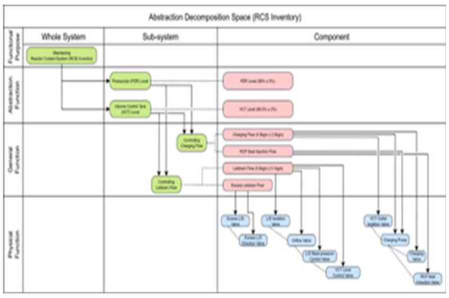

Fig. 1. ADS diagram for maintaining RCS inventory.

3. Development of ADS-based Operator Action Support Algorithm

This section describes the design of the operator action support agent based on the ADS analysis results from Section 2. The proposed system maps the ADS hierarchy onto the core components of DRL: the state space, action space, and reward function.

3.1. Methodology

In this study, proximal policy optimization (PPO) is employed as the DRL agent. The clipping mechanism, a key feature of PPO, restricts the policy update ratio to prevent abrupt shifts or bias toward specific data during training. This ensures convergence stability, enabling the agent to learn robust optimal policies across diverse abnormal scenarios without policy collapse.

The PPO agent in this study interacts with a compact nuclear simulator (CNS) to experience various abnormal scenarios and derives optimal action through an actor-critic architecture. Furthermore, the reward function is designed to reflect the hierarchical dependencies of the ADS, where the ultimate functional purpose is maintaining the RCS inventory through the coordinated control of sub-functions, such as PZR and VCT levels.

By embedding this functional hierarchy into the learning process, the agent is trained to identify dynamic functional priorities—evaluating whether the PZR or VCT level requires more immediate intervention depending on the specific nature of the abnormal transient.

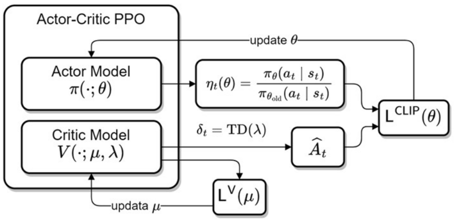

Fig. 2. Policy clipping mechanism in PPO. [6]

3.2. Training and Experiment

For a real-time testbed to train the DRL agent and develop the ADS-based operator action support system, CNS was utilized (see Fig. 3). The CNS reflects the plant's dynamic characteristics under abnormal scenario, providing environment for the agent to collect data and learn across various abnormal scenarios.

Fig. 4 illustrates the training performance, showing the convergence of steps per episode and cumulative reward over episode. In the early stages of training (up to episode approximately 60), the agent exhibited low reward. However, a significant performance improvement was observed after 63 episodes. After episode 100, both the reward and the step count in each episode reached a steady plateau, demonstrating that the ADS-based reward function effectively guided the PPO agent to prioritize functional integrity. This convergence in a relatively small number of episodes proves the efficiency of embedding the ADS hierarchy into the DRL framework.

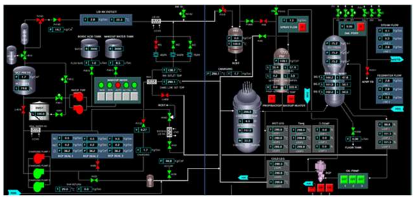

Fig. 3. Mimic interface of CNS simulator.

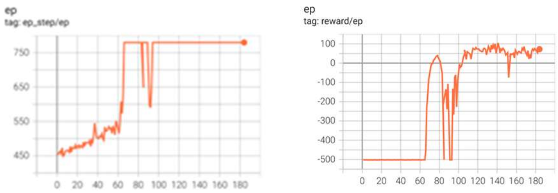

Fig. 4. Convergence of the DRL agent in terms of steps per episode (left) and cumulative reward (right).

3.3. Human-System Interface for Action Support

This section describes the configuration of the human-system interface (HSI), designed to visualize and deliver the optimal action derived by the DRL agent to the operator. The upper and middle sections of the left panel display real-time abnormal alarms and system symptoms to support the operator in performing a topological search to identify the physical origin of the anomaly. In the right section, the interface provides a system mimic display and an ADS tree view, which are switchable via tabs to allow operators to interchangeably refer to cross-reference the physical connectivity with the hierarchical functional structure.

The action recommendation area, located in the bottom-left panel, provides specific interventions suggested by the PPO agent. To include causal transparency, the interface provides the underlying rationale for each action by mapping it to the ADS hierarchy. These rationales are presented in a table format as follows: 1) the unsatisfied system function (functional purpose), 2) the operational goal (abstract function), 3) the required function to achieve the operational goal (generalized function), and 4) the necessary action for the required function (physical function).

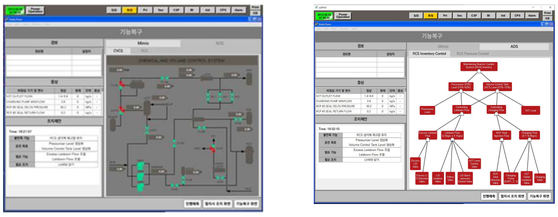

Fig. 5. GUI interface of ADS-based operator action support system.

4. Conclusion

This study developed an ADS-based operator action support system to provide real0time optimal recovery actions and their underlying rationales during abnormal operation. By integrating the functional hierarchy of the ADS into a DRL framework, the system enables the agent to perceive and evaluate plant states in hierarchical structure rather than a simple collection of numerical data. Furthermore, the developed HIS provides causal guidance by allowing operators to cross-reference recommended action and ADS tree views. This integrated methodology suggests a domain-informed approach to decision support, which has the potential to guide operators through complex functional structures when procedural gaps occur.

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