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Functional Requirements of an Intelligent Decision Support System Prototype in Korean NPPs Under Normal and Abnormal Conditions

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1. Introduction

The Intelligent Decision Support System (IDSS) for the Korean Nuclear Power Plant (NPP) under normal and abnormal conditions facilitates the decision-making process of the main control room operator by monitoring and diagnosing conditions, predicting progress, and providing preventive advice. By visualizing information, the system reduces the operator's cognitive load. Additionally, it presents data on system-generated results and their underlying rationale, thereby enhancing decision-making and minimizing human errors (Figure 1). Currently, a prototype of the IDSS is being designed and developed to validate its functionality and performance.

2. Development and Operation Concept of the IDSS

Jang and Koo (2024) identified key design challenges in applying the fundamental technology of an IDSS, as well as the necessary design and validation technologies for its implementation. Additionally, their study aims to establish preliminary technology-specific management plans to address each design challenge [1].

The IDSS functions as a data-driven operator advisory system that does not involve control actions. The role of IDSS in the main control room is illustrated in Figure 1. The IDSS is designed as a subsystem of the Information Processing System (IPS) for Korean NPPs. Accordingly, it is classified as a non-safety system and an electrical non-class 1E system. If implemented within the Man-Machine Interface System (MMIS) of Korean NPPs, the IDSS must adhere to the software grade classification system specific to these plants. Depending on its operating environment, the software classification of IDSS is designated at the Important to Availability (ITA) level and the General Purpose (GP) level.

The IDSS is designed using data-driven and deep neural network-based algorithms to enhance robustness and predictive accuracy across various measurement variables encountered under diverse NPP conditions. It predicts plant behavior based on reliable signals, diagnoses the current state, and calculates the remaining reactor trip time, thereby informing operators of the available response window. In single abnormal scenarios, it recommends actions in accordance with procedural guidelines, while in complex situations, it suggests optimal functional recovery strategies.

The IDSS operates within a secure development environment—which includes a nuclear big data platform and a deep learning model platform—as well as a secure operational environment—comprising an IDSS server and a human-system interface, as illustrated in Figure 2. In future implementations, development environment equipment will be located outside the NPP, whereas operational environment equipment will be positioned in the control room and computer room within the auxiliary building of the NPP. The secure development process, conducted externally, involves iterative cycles of data management, analysis, model training, and performance evaluation using the big data and AI platforms. The resulting AI models and algorithms are distributed as software through containerization, leveraging a microservice architecture. Meanwhile, secure operations within the power plant are facilitated by integrating IDSS display pages into the information display screen layer of the dual IDSS server, which is housed in both the computer room and the main control room control panels.

3. Structure and modules of the IDSS Prototype

The IDSS prototype comprised a big data platform, an artificial intelligence platform, an IDSS server, and a Human-System Interface (HSI), as shown in Figure 3. Unlike actual implementation in an NPP, the prototype did not differentiate between internal and external environments and configured a separate communication network.

The big data platform and artificial intelligence platform shared a common data storage within the same network. This system played a critical role in analyzing power plant data, diagnosing and predicting plant conditions using an AI-based decision-making model, and providing operators with appropriate recommendations. The big data platform included modules for data collection, clustering, storage, analysis, validation, and visualization to supply training data for the deep learning platform. The artificial intelligence platform incorporated modules for model training, testing, validation, and visualization, ensuring the AI model could be deployed to the IDSS server. The IDSS server performed signal validation, abnormal condition diagnosis, progress prediction, and preventive action support using a deep learning model. It provided relevant information to the operator via the IDSS HSI. The displayed information included module outputs, early warnings, trip variable predictions, procedure- and system-based action support, and model confidence levels with thresholds. Additionally, the IDSS was designed to activate a safe mode if performance requirements were not met. To ensure reliability, the system incorporated response reliability assessment and data robustness modules.

4. Functional Requirements of the IDSS Prototype

The preliminary functional requirements for the IDSS prototype described below will be modified and supplemented as the prototype development progresses.

4.1 Big data management function

- Data Collection and Loading: Real-time data collection, high-speed loading, and error control functions. Signal integration and large-scale data loading/integrity assurance are required.
- Data Exploration and Preprocessing: Handling missing values, removing outliers, analyzing variable correlations, providing data visualization and basic statistical values.
- Data Labeling and Imbalance Handling: Manual/automatic labeling, validation functions, imbalance analysis and solutions (data augmentation, oversampling, ensemble learning).
- Data Cataloging: Automatic generation of metadata, management of data source/type/purpose, and data lineage tracking.
- Data Integration/Sampling/Feature Selection: Data integration, resolving redundancy/consistency issues, sampling techniques, and feature selection algorithms to maximize model learning efficiency.
- Data Storage: Secure storage of large-scale data, automatic capacity expansion, backup/recovery, enhanced security, and real-time search/edit functions.
- Big Data and Metadata Configuration Management: Management of the data lifecycle, version control, tracking of changes, and configuration management features.
- Platform Management: Fault detection, recovery, resource monitoring and optimization, automatic actions in case of resource shortages.
- Big Data Platform Security Control: Access control, encryption, authentication procedures, security auditing, and threat detection/alert functions.
- Big Data Validation: Data documentation by producers, validation for data quality assurance, and practical application of quality management requirements.
- Visualization: Visualization of large datasets, provision of user-defined dashboards, and support for decision-making.

4.2 AI modeling and analysis function

- AI Model Training: Trains deep learning models based on large-scale time-series data. Supports various learning algorithms, GPU acceleration, real-time monitoring, and flexible stopping/restarting. Supports automated hyperparameter tuning, data augmentation, and windowing techniques.
- AI Model Testing: Evaluates model performance: Classification models (accuracy, F1 score, precision, recall) and time-series models (error calculation, man absolute error, root mean square deviation). Provides real-time visualization and performance enhancement features.
- AI Model Validation & Model Validation: Assesses model overfitting and generalization capability. Supports cross-validation, K-fold, and holdout validation. Rolling window method for time-series data validation. Independent validation and robustness testing (considering sensor channel aging).
- Summary and Visualization of Model Training/Testing/Validation: Summarizes model training, testing, and validation results in text, graphs, and tables. Provides ROC curves for classification models and time-series graphs for time-series models. Supports smooth visualization even with large datasets.
- AI Model Storage: Safely stores results and metadata from training, testing, and validation. Supports version management and history tracking, data compression, and encryption. Fast recovery functionality. Efficient management of time-series data per timestamp.
- AI Model Registration & Configuration Management: Registers final models and manages metadata. Tracks changes to models and code through a configuration management module. Automates model deployment and provides fast recovery in case of issues.
- AI Platform Management: Real-time monitoring of system status, fault detection, and response. Collects logs and provides real-time alerts. Implements security controls and access management. Efficient resource management with auto-scaling.
- Model Robustness: Ensures robustness against adversarial attacks. Considers natural sensor channel aging and drift for robustness evaluation.
- Result Derivation Process & Explanation: Provides model reliability and uncertainty information. Uses XAI (Explainable AI) technology to visualize the reasoning behind model inferences and outputs.

Provides alternative methods if XAI cannot be applied.

- Integration with Big Data Platform: Accesses Ceph-based big data storage and efficiently processes data through integration with distributed file systems.
- Integration with IDSS Servers: Supports stable real-time communication between the IDSS server and the dashboard of HSI devices. Ensures immediate data synchronization, provides backup paths for data loss prevention, and automatically recovers in case of errors.
- Communication & Integration: Real-time data synchronization between servers, with emphasis on communication speed and accuracy. Provides automatic recovery in case of errors during data transmission. Ensures a stable network connection.
- Testing & Maintenance: (Testing): Generates training data using APR1400 simulator, simulates real nuclear environment, and evaluates human-factor effectiveness. Periodic performance evaluations under normal and fault modes. Prepares test plans and reports. (Maintenance): Modular development, tracking performance changes due to data changes, and performance evaluation. If needed, retraining or model redesign based on new data. Flexibility to quickly reflect changes in the decision-making environment.

4.3 Decision support and HSI function

- Signal Validation and Restoration Module: Analyzes collected data to assess signal integrity and detect anomalies. Restores damaged data to provide reliable data
- Anomaly Detection Module: Detects abnormal situations in real-time and integrates with the warning system to notify operators. Provides reasoning for anomaly detection.
- Abnormal State Diagnosis Module: Analyzes abnormal states of the plant using diagnostic algorithms and provides results to operators for appropriate response.
- Progress Prediction Module: Predicts changes in key plant variables and reactor shutdown times. Helps operators take timely actions by anticipating potential issues.
- Preventive Action Support Module: Provides suggested actions based on procedures and optimal recovery solutions for operators. Helps prevent the escalation of abnormal situations.
- System Risk Management: Manages potential risks during system development and operation. Addresses security issues with open-source software.
- System Safe Mode: Automatically switches to safe mode in case of errors or performance degradation. Provides warnings and IDSS control functions for operators to take appropriate action.
- User Interface and Page Configuration: Provides intuitive dashboards and user-customizable settings. Uses graphics to clearly convey information and allows operators to adjust page layouts and warnings. Supports error detection and quick response capabilities. The decision support function page of the IDSS starter product consists of the main page, which contains the XAI page contents, and its sub-pages. The main page aims to provide alarms, procedures, and system diagnosis results.
- Key Intelligent Decision Support & Warnings: Provide hierarchical plant data, XAI-based diagnostics, and predictive warnings. Display clear warnings, visualized trip predictions, and corrective actions. Present diagnostic results and recovery steps with intuitive visuals.
- Display Function Management: Enable operators to customize dashboard views and filter information. Ensure intuitive HSI design for quick response. Provide visual and auditory signals with user-friendly UI/UX.
- Integration with IDSS Server: Maintain real-time, stable communication between the dashboard and server. Ensure continuous data synchronization. Implement automatic recovery from communication failures to prevent data loss.
- Communication & Integration: Ensure fast and accurate data synchronization for decision-making. Minimize communication latency. Auto-correct data transmission errors for high reliability.
- Testing & Maintenance: Conduct testing using the APR1400 simulator under various conditions. Implement continuous performance monitoring and modular system design. Track AI model versions and evaluate new data integration for accuracy.

5. Conclusions

An IDSS for the Korean NPP is being developed to enhance decision-making and reduce human error in the MCR under both normal and abnormal operating conditions. A prototype is currently under design and development. This paper first identified development and operation concept of the IDSS and structure and modules of the IDSS prototype. Second, this paper pre-defined functional requirements for each detailed module within the scope of the IDSS prototype implementation.

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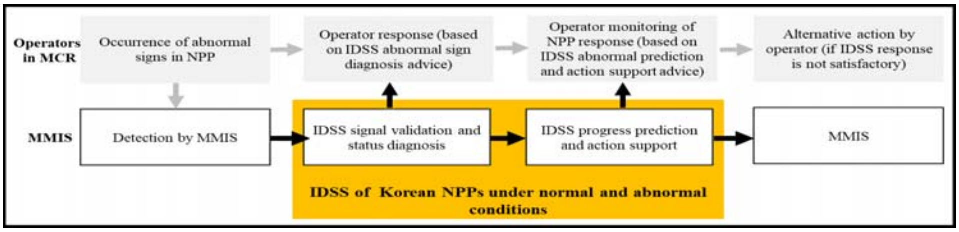

Fig 1. Role of the IDSS in Korean NPPs under normal and abnormal conditions

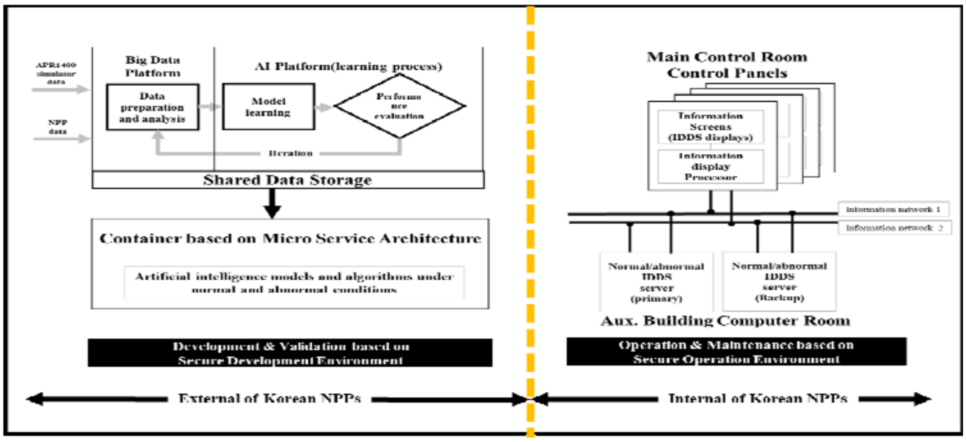

Fig 2. IDSS development and operation for Korean NPPs

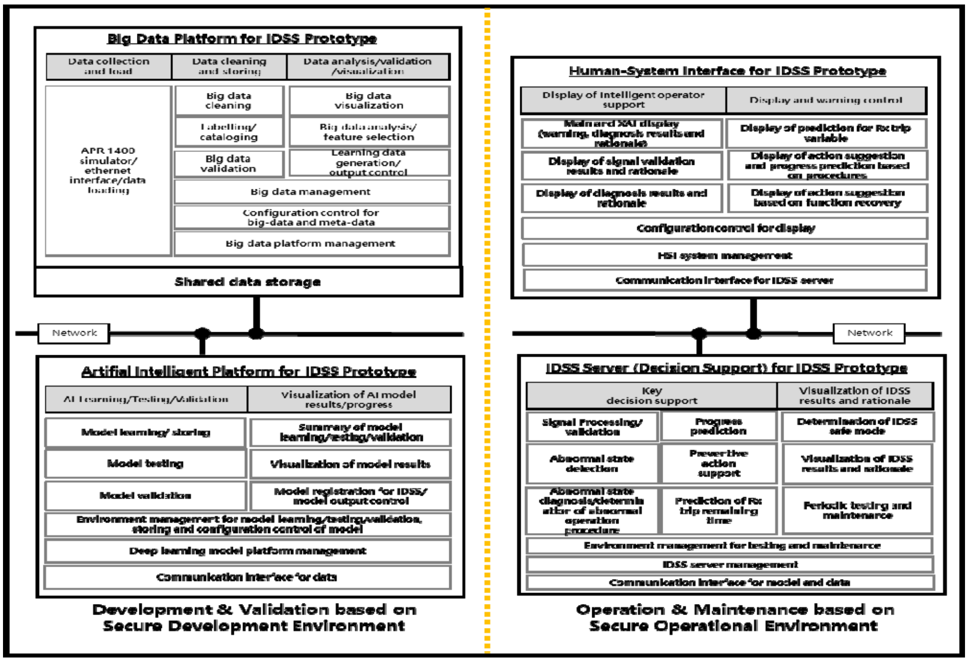

Fig 3. Structure and modules of the IDSS prototype