Functional Requirements of SMR Digital-Twin Framework

Sung Won Lim [a*]
[a]*Korea Atomic Energy Research Institute, (34057) 111, Daedeok-Daero 989Beon-Gil, Yuseong-Gu, Daejeon, Korea*
[*]*Corresponding author: sw54176@kaeri.re.kr*

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1. Introduction

Since the discovery of nuclear fission, nuclear energy has provided a reliable source of electricity for decades. Recently, however, rapid advances in artificial intelligence (AI), the resulting growth in electricity demand, and the increasing need for low-carbon energy to address climate change have significantly renewed interest in nuclear power. In response to these changes, several organizations and companies are making substantial investments in Small Modular Reactors (SMRs) and conducting extensive research to strengthen their technological competitiveness [1]. Amidst this global trend, SMR technology using AI-based digital-twins has been proposed. The purpose of this study is to define the performance objectives required for SMR operation based on existing NRC digital-twin research, systematically derive functional requirements to achieve them, and establish a basis for developing the SMR digital-twin framework.

2. Digital-Twin Technology for SMR

2.1. Overview of Digital-Twin Technology

In simple terms, a digital-twin is a digital replica of a physical system or process in the real world within a virtual space. The purpose of these digital replicas is not merely to serve as static models, but to reflect the state, behavior, and interactions of real-world systems in real-time or near-real-time, thereby enabling advanced analysis and decision-making throughout the entire process of design, operation, and maintenance.

The concept of digital-twin is believed to have first emerged in 2003 during Professor Grieves's Product Lifecycle course [2]. Although the concept was not sufficiently specific at the time, it proposed that a preliminary form of digital-twin consists of three parts: A. a physical product, B. a virtual product, and C. the connection between the two. Since then, the concept of digital-twin has been developed in various industries, including aerospace, manufacturing, energy, and infrastructure, and its potential for application in the nuclear industry is also gradually being suggested.

2.2. Application of Digital-Twin Technology to Nuclear Power

According to the NRC technical report [3], the nuclear digital-twin is structured around three core components. First, the physical asset refers to the actual equipment and operating environment of the nuclear power plant. Sensors and instrumentation installed on major facilities, such as the reactor, turbine, and coolant system, generate real-time data, and this information forms the basis of the digital-twin. Second, the digital model is the area that reproduces the physical equipment in a virtual space, integrating various techniques such as engineering simulation, AI analysis, and probabilistic safety models. This model precisely simulates the dynamic state of the physical system by predicting and reproducing the thermal-hydraulic behavior, structural behavior, and control logic of the actual equipment. Third, the data link is responsible for the bidirectional connection between the physical asset and the digital model. This layer plays the role of transmitting data collected from sensors to the digital-twin in real time and reflecting the analysis results back into the control and operational decision-making of the physical asset. These three components are integrated into a closed-loop feedback structure. The NRC emphasizes that through this structure, the digital twin can extend beyond simple monitoring to perform prediction, optimization, and control functions. Ultimately, the nuclear digital-twin is defined as an intelligent operation and decision support system that simultaneously improves operational safety and efficiency by connecting and analyzing the complex equipment and operational data of a power plant in real time.

2.3. Application of Digital-Twin Technology to SMRs

Many SMR designs are expected to provide flexible load-following capabilities to facilitate integration with variable renewable energy sources. In addition, to improve the economic efficiency of construction and operation, SMR designs generally adopt modular deployment concepts in which multiple reactor modules can be constructed and operated at a single site. Some SMR designs also employ an integrated control concept that enables multiple reactor modules to be monitored and controlled from a single control room. These characteristics distinguish SMRs from conventional large-scale nuclear power plants and should therefore be appropriately considered when applying digital-twin technology to SMRs [4].

Considering these operational characteristics, an SMR digital-twin should be capable of rapidly predicting the current and up-coming states of the reactor and associated systems based on the real-time acquisition and analysis of operational data. It should also support optimal operation by evaluating changes in plant conditions and providing appropriate operational responses, particularly during load-following operation and transitions in operating conditions. Furthermore, information obtained from multiple reactor modules, together with the corresponding analysis and prediction results, should be integrated and provided to operators through the integrated control room to support effective monitoring, decision-making, and operation of multiple modules.

3. Requirements of SMR Digital-Twin Framework

3.1. Definition of the SMR Digital-Twin Framework

The previous section discussed the key characteristics that should be considered when applying digital-twin technology to SMRs. Although the functions provided by digital-twin technology should be integrated, managed, and utilized within an integrated control room, an important consideration from a reactor safety perspective is that these functions should be implemented and operated independently from the systems responsible for direct reactor operation and control. Such separation is necessary to ensure that the application of digital-twin technology does not adversely affect the safety and reliability of the existing reactor operation and control systems.

From this perspective, in this study, the SMR Digital-Twin Framework is defined as an independent system established using digital-twin technology to provide integrated support for SMR operation. The framework integrates the acquisition and analysis of operational information, prediction of plant states, and support for optimal operational decision-making, while remaining functionally separated from the systems that directly operate and control the reactor. Based on this definition, Fig. 1 illustrates the conceptual structure of the proposed SMR Digital-Twin Framework and its functional relationship with the SMR physical systems and the operator.

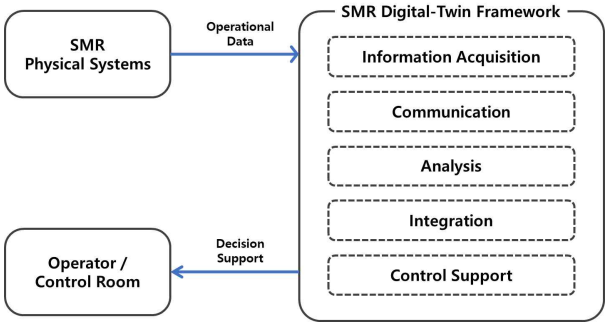


Fig. 1 Conceptual structure of the proposed SMR Digital-Twin Framework

3.2. Performance objectives of SMR Digital-Twin Framework

The NRC's technical report defines the digital-twin not as a simple simulation tool, but as a real-time predictive reactor operation platform that integrates design, operation, and maintenance management and supports operational decision-making based on collected and reproduced data [5].

Based on this concept, the definition of the SMR Digital-Twin Framework presented in Section 3.1, and the SMR-specific operational characteristics discussed in Section 2.3, four performance objectives are established to provide integrated support for SMR operation as follows:

A. Comprehensive Operation Information Analysis and Display
B. Rapid Operational Simulation Capability for Normal and Abnormal Conditions
C. Optimal Operational Response Suggestion Capability
D. Operational Decision and Control Support Capability

3.3. Functional Requirements of SMR Digital-Twin Framework

To develop an SMR digital-twin framework that achieves the performance objectives presented in Section 3.2, these performance objectives need to be further translated into functional requirements. The functional requirements presented in this section represent a classification of the detailed functional elements that the digital-twin framework should provide. In practice, the SMR digital-twin framework is implemented as an integrated system consisting of various models and components that collectively satisfy these functional requirements.

Based on this functional decomposition which is shown in Fig. 1, the functional requirements of the SMR digital-twin framework are classified into the following

five categories: information acquisition, communication, analysis, integration, and control support.

A. Information Acquisition: The first functional requirement of a SMR digital-twin framework is the information acquisition function, which detects and collects various information from the physical assets in real time. This serves as the starting point for a SMR digital-twin framework. Since nuclear power plants are composed of multiple complex subsystems, such as thermal-hydraulic systems, fuel systems, and auxiliary facilities, it is crucial to collect accurate and sufficient operational data of each subsystem.
B. Communication: The second functional requirement, communication, transmits data collected through information acquisition to analysis modules within the digital-twin framework. It represents the core channel for a bidirectional flow that provides analysis results to the physical assets or the operator. The communication function is an advanced component that goes beyond simple data transmission to simultaneously ensure speed, accuracy, security, and interoperability.
C. Analysis: Third, the analysis function is the core function of the digital-twin framework. It includes cognitive functions that utilize collected data to diagnose the current state, predict future states, and propose optimal operating actions or control strategies. Analysis is divided into physics-based and data-based approaches, and the convergence of the two drives the implementation of an intelligent digital-twin. The physics-based modeling corresponds to traditional numerical analysis and simulation techniques, with representative methods such as the Finite Element Method, Finite Volume Method, and Finite Difference Method. On the other hand, data-based analysis refers to prediction models based on machine learning or deep learning.
D. Integration: The fourth functional requirement, integration, is a meta-function that organizes all components within the digital-twin framework into a single consistent platform. This requires multidimensional integration that goes beyond simple system connectivity, encompassing data consistency, time synchronization, functional consistency, and user experience. Generally, nuclear power plants contain a mix of systems from various vendors and proprietary protocols; therefore, it is crucial to integrate these components to ensure uninterrupted information flow throughout the entire lifecycle of design, operation, and maintenance.
E. Control Support: The final functional requirement, control support, is to support operator decision-making based on analysis and prediction results. This represents the final stage of digital-twin utilization and is linked to core functions of autonomous operation or predictive maintenance strategies. Therefore, appropriate protection measures, such as fail-safe design, verification of control algorithms, and functional independence from safety systems, should be considered in implementing the control support function.

4. Conclusion

In this study, the characteristics of SMRs that should be considered in applying digital-twin technology were identified, and the SMR Digital-Twin Framework was defined as an independent system that provides integrated support for SMR operation. Based on this definition and the operational characteristics of SMRs, four performance objectives were established for the SMR Digital-Twin Framework.

To achieve these performance objectives, five functional requirements were identified: information acquisition, communication, analysis, integration, and control support. These functional requirements represent the key functional elements required to implement the SMR Digital-Twin Framework and provide a basis for developing its detailed system architecture.

Future work will focus on developing the detailed architecture of the SMR Digital-Twin Framework based on the functional requirements identified in this study. The developed framework is expected to support the safe and efficient operation of SMRs and contribute to improving their operational and economic competitiveness.

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