# Research on intelligent operation and maintenance technology for small modular reactor

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**Abstract**

This article presents an in-depth study on the application of digital technology in the operation and maintenance stage of the SMR. It focuses on intelligent operation control, monitoring and diagnosis, inspection and surveillance, maintenance management, and other aspects to enhance the automation and intelligence of operation and maintenance.

## **Background and Necessity**

Due to its inherent safety, flexible deployment, and wide range of applications, Small Modular Reactor (SMR) have garnered continuous attention and follow-ups from both domestic and international markets. With the power scale of SMR and their suitability for deployment in remote areas like islands and mountainous regions, integrating intelligent operation control, monitoring and diagnosis, inspection and surveillance, and maintenance management technologies can further enhance the automation and intelligence levels of SMR. This can lead to reduced operation and maintenance costs and address the demands and challenges of global advanced energy development by offering higher safety and economic efficiency.

## **Project Requirements**

The digital intelligent operation and maintenance of SMR aims to ensure nuclear safety through technologies including but not limited to virtual-physical mapping and real-time interaction, large-scale multi-modal data collection for operation and maintenance, intelligent warning and fault diagnosis based on mechanism models and data analysis, predictive maintenance, AI applications for digital twin technology, etc. By building a digital twin asset foundation and intelligent operation and maintenance application system, allow it achieve unified management of data assets. Also, based on this data foundation, real-time monitoring, trend prediction, warning analysis, fault diagnosis and location, decision optimization, etc., are implemented for the operating status of nuclear power system or equipment. The ultimate goal is to establish an "unmanned monitoring, less manned operation", to ensure continuous and stable operation of the plant, reduce the risk of shutdown, and further lower the total cost of the operation and maintenance. In addition to serving core business areas such as operation management and maintenance management, the project value is expanded to design management, engineering management, commissioning management, modification management, operation management, etc., and eventually exploring the establishment of full-life management of power plants.

## **Solution**

### Overall Technical Architecture

The digital twin system of SMR needs to integrate various mechanism models such as reactor physics, thermal-hydraulics, structural mechanics, power distribution, equipment system health, and faults diagnosis, combining the complex working mechanism of the nuclear power plant production system with digital models to ensure its authenticity and precision. Through virtual-physical mapping, the operation status, operational parameters, design parameters, and simulated trend data of the nuclear power plant are mapped to a virtual environment for monitoring, analysis, and optimization by personnel or advanced applications, achieving seamless connection and mutual representation between the real nuclear power plant and digital models and applications, reaching the ecological stage of digital twins. With the contribution of real-time interaction technology, a data interaction platform that can respond instantly and efficiently is constructed between the digital control system, real-time data acquisition system, intelligent diagnosis and warning system, and remote monitoring and operation system to improve the operational efficiency and safety management level of the nuclear power plant. In addition, by extending to the comprehensive mapping of systems, structures, and even the entire layout of the nuclear power plant, providing all-round operational maintenance guidance and intellectual support for staffs at all levels in various stages such as commissioning, operation, and outages.

### Applications

#### Digital Delivery

Through a digital platform for collaborative design, data collection, management and utilization are applied from the design stage, such as construction simulations and smart construction site applications, avoiding repetitive construction, and enhancing safety and efficiency of on-site operations.

#### Physical Factory Twin Application

Realizing navigation and visualization of physical assets, integrating design, construction, and operation data, providing real-time decision support for engineers, operators, and maintenance workers in various stages of the nuclear power plant life-cycle.

#### Equipment Twin Application

Based on digital twin asset management, from the perspective of full life-cycle management of equipment, achieving performance improvement in equipment operation, maintenance, procurement, etc., enhancing equipment availability and capital utilization rate.

#### Process Twin Application

Integrating process models with real-time and historical data, utilizing historical data, and deeply combine with cutting-edge technologies such as artificial intelligence, intelligent control and decision-making to monitor and optimize asset production performance.

#### End Twin Application

Through integrated optimization of technology and processes, combining various engineering technologies such as intelligent devices, industrial robots, internet of things (IoT), artificial intelligence, virtual augmentation, etc., strengthen basic skills and empowering staffs to complete production tasks timelier, efficiently, and safely.

### Scene

Establishing designing, operating, and managing data centers as the cornerstone to carry the integrated data of nuclear power plants from design, operation, maintenance to management, creating specialized high-precision digital twin models to lay the data foundation for building a digital twin factory.

The core of intelligent operation and maintenance is the research and utilization of various sensors, data collection devices, and algorithms to monitor and analyse the operating status of system equipment in real time. Through these data, specific equipment anomalies and potential faults in related systems can be detected timely, enabling a more flexible and cost-effective preventive maintenance strategy to avoid or reduce system downtime. By continuously upgrading and iterating intelligent operation and maintenance technologies, these strategies can be continuously developed and improved.

#### Real-time monitoring module of equipment/system operation status

Using sensors and data collection devices installed at critical parts of the plant to monitor operation status in real time. Through an intelligent inspection system, automated inspections of various systems and equipment at the nuclear power plant are conducted regularly, collecting data from multiple dimensions throughout the entire cycle and transmitting the data in real time to the system platform for integration, disposal, and utilization. This not only reflects the real-time operating status of the nuclear power plant but also provides important data sources for advanced applications such as fault prediction and preventive maintenance.

#### Operation digital scenario

Based on the data foundation mentioned above, the intelligent operation platform integrates big data, mechanism modelling, machine vision algorithms, etc., to build intelligent operation applications quickly and efficiently. Specific components include intelligent operation decision support, intelligent control optimization, warning and diagnosis, intelligent procedures, knowledge and experience management, etc.

#### Maintenance digital scenario

By comprehensively using advanced information technologies such as big data, artificial intelligence, and IoT, intelligent transformation and enhancement of the processes are carried out to create an intelligent operation and maintenance technology platform for equipment and systems. This platform aims to improve the efficiency and quality of equipment maintenance, reduce costs, and enhance the stability and safety of nuclear power plant operations.

### Digital Twin Base Construction Technology

#### Based on data architecture and information model analysis

Digital delivery standards applicable to SMR or equivalent scale nuclear units are developed to meet the full life cycle control requirements of construction and operation. This includes exploring the construction strategy of high-precision digital models, covering elements such as accurate model establishment, integration and synthesis, dynamic correction, and comprehensive verification. Building a data-driven, virtual-real combined, and mutually mapped digital twin system to establish standards and norms for mass construction and industrial promotion.

#### Digital technologies for the entire process of handover and production transfer for SMR

Including but not limited to handover and production transfer plan management, TOM (Take Over for Maintenance) management, TOTO (Take Over for Temporary Operation) management, BHO (Building Hand Over) management, and joint inspection observation item management, to enhance the effectiveness and compatibility of data flow in various stages throughout the life-cycle of plants.

#### Multi-source heterogeneous data and 3D lightweight visualization technology

Based on the nuclear power plant's main body objects, with data integrated management as the core, and considering the full life-cycle of the nuclear power plant, research is conducted on the mapping relationship of design data, engineering data, and operation and maintenance data. Research on multi-source heterogeneous data and 3D lightweight visualization technology aims to form a new model of visual control based on the integrated data assets, enabling a user-friendly experience for convenient use and maintenance.

#### In-depth research on the application scenarios of digital twin technologies in various business areas

Based on the digital twin data foundation of SMR, continuous research is conducted on cutting-edge application scenarios in engineering, operation, maintenance, and other business domains.

### Intelligent Operation Technology

In-depth development of multi-dimensional operation health assessment for nuclear power plants, intelligent diagnosis integrating mechanism, data and knowledge, automated operation procedures, process control optimization technology, nuclear power plant robotics, and large-scale experience feedback models, including:

#### Multi-dimensional operation health assessment technology

Evaluates the operation health status of units, systems, and equipment at multiple levels from safety, stability, prediction, control, and economic perspectives. It forms a quantifiable assessment matrix and provides a hierarchical drilling display interface to comprehensively demonstrate the overall health evaluation status of the unit. It also keeps the traceability of specific reasons affecting the health status of the unit, reducing the workload on personnel.

#### Mechanism, data and knowledge integration diagnosis technology

Based on predictive diagnostic analysis models specific to production processes. It combines various intelligent analysis algorithms such as nonlinear evaluation, vector regression, neural networks, etc., and studies real-time diagnostic methods for process deviations, abnormal statuses, and equipment failures during unit production processes. It can timely warning and intervention in the early stages of anomalies, providing crews with sufficient handling opportunities to avoid further losses from accidents.

#### Automated operation procedure technology

Studies the automatic execution of overall procedures, system procedures, periodic test procedures, and explores automatic deployment of breakpoints and secure rollback mechanisms for procedure execution exceptions. By combining fault warning, alarm combination analysis, accident consequence deduction algorithms, and using real-time unit alarm information, it provides alarm procedures, abnormal operation procedures, and accident operation guidance. It optimizes the revision process of technical documents in nuclear power plants, explores the logic implementation from demand changes to document execution in automatic procedure mode, and enhances the agility and usability. It achieves automatic execution of processes such as reactor start up and shutdown, turbine start up and shutdown, output changes, and periodic testing, as well as assists decision-making in handling anomalies, reducing the probability of human errors and skill requirements during anomalies or accidents, and improving the safety of nuclear power plant operations.

#### Nuclear power plant control optimization technology

Conducts research on control algorithms for all equipment in nuclear power plants, such as model predictive control algorithms, adaptive control algorithms, optimal control algorithms, fuzzy control algorithms, neural network control algorithms, reinforcement learning control algorithms, etc. These algorithms are applied in areas such as coordinated control of the reactor-turbine, steam generator water-steam balance control, and generator primary frequency control. Simultaneously, it researches methods for evaluating the running status of control systems in plants, using methods such as minimum variance evaluation, loop oscillation detection, process non-linearity detection, and IMC parameter tuning to systematically evaluate control systems and provide improvement suggestions. Furthermore, it enhances the stability of various control systems in plants, reduces safety hazards and accuracy losses caused by manual adjustments.

#### Nuclear-specific robotics technology

Researches component-based design and high reliability of core components in the industrial scenarios of the SMR, as well as quick plug-and-play technology. It focuses on automation technologies in inspection and maintenance fields, utilizing various sensors such as video cameras, audio probes, infrared sensors, and radiation field sensors to automatically identify on-site abnormal states, monitor the spatial distribution of radiation fields, and reduce or replace daily inspection and risky area operation.

#### Experience feedback system

Researches the adaptability training technology of large models in the nuclear power industry, such as experience feedback collection, operation, and maintenance support applications. It achieves automatic collection of experiential knowledge, provides targeted learning courses and materials for different employees in the operation, inspection, and maintenance professional fields, and offers interactive intelligent voice assistants.

### Intelligent Maintenance Technology

Research focuses on multi-dimensional data fusion for system equipment operation and maintenance in nuclear power plants, early warning of critical system/equipment and self-diagnosis of faults, and intelligent inspection technology under complex operating conditions. This includes:

#### Multi-dimensional data fusion technology for system equipment operation and maintenance in nuclear power plants

Research on extracting features related to equipment operation status and performance from multi-dimensional data. It utilizes statistical methods, signal processing, or machine learning algorithms for feature selection to determine the most contributing factor set for operation and maintenance decisions. It integrates multiple data sources effectively to enhance the comprehensive understanding and evaluation of equipment status. It develops data fusion methods based on weight, probability, or fuzzy logic to enhance the confidence and information content of the data.

#### Early warning of critical system/equipment and self-diagnosis technology for faults

Research on intelligent management of system equipment health, intelligent monitoring and diagnosis of key system equipment, intelligent spare parts inventory management, and intelligent preventive maintenance strategies for system equipment. Study fault diagnosis technologies based on pattern recognition, machine learning, or deep learning to accurately identify and classify system equipment failures. Research predictive models that combine historical data and real-time monitoring data to evaluate equipment remaining life and potential failure risks.

#### Intelligent inspection technology under complex operating conditions

Research on intelligent inspection robots for system/equipment of SMR, achieving automatic inspection, instrument reading recognition, equipment alarm recognition, medium leakage detection, and abnormal sound detection. It enables artificial intelligence monitoring and early warning of operational status, coordinate with the work request system, and automatically submits work requests for abnormal status.

### Platform Development

* Digital twin platform with "unified standards, unified models, and unified services".
* Equipment system intelligent operation and maintenance canter platform with "integrated monitoring, intelligent analysis, and unified management".
* Real-time data collection and monitoring system for equipment system operation.
* Virtual Reality or Augmented Reality technology-supported remote cooperation and maintenance guidance platform.
* Intelligent operation platform.
* Robots that meet the requirements of radiation environments, with functions including fast component plug-in, visual recognition, audio analysis, infrared analysis, and robotic arm operation capabilities.
* Large model based on feedback training from nuclear power plant experience, with intelligent voice interaction capability.

## **Summarizing**

Small nuclear reactors have the advantages of small power output and suitability for deployment in remote areas. However, the operational maintenance stage is heavily reliant on manual operations, which is not conducive to enhancing safety performance. Additionally, the high labour costs significantly impact the economic viability. In order to meet the global demand and challenges of advanced energy development with higher safety and economic efficiency, this article discusses the digital intelligent operation and maintenance technology for small nuclear reactors. This technology can enhance the automation and intelligence level of SMR operation and maintenance, reduce manual operations, decrease human errors, lower labour costs, improve operational safety and economic efficiency.