Utilizing digital twins for nuclear safeguards and security

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Abstract

Near-term nuclear industry innovations in reactor design and construction create new challenges in applying nuclear safeguards and deterring and streamlining the detection of nuclear proliferation (i.e., diversion and misuse) as these technologies are deployed more broadly. These challenges relate to the broad adoption and acceptance of next-generation technologies and techniques for proliferation detection, as state-of-the-art methods advances beyond long-established standards.

Digital twins have the potential to improve the effectiveness of international safeguards inspectors by providing a tool that can: perform an accurate diversion pathway analysis, identify the pathway indicators, develop the required sensors to detect those indicators, and monitor facilities in real time using critical data streams that benefit from this safeguards-by-design approach. Safeguards inspectors are required to visit facilities and verify the nuclear material to ensure no diversion has taken place and to detect misuse of the facility; however, this analysis and verification effort requires significant expertise, time, and funding. It is imperative that inspector time spent at a nuclear facility is focused on key areas that require hands-on activities.

Digital engineering embodies a deliberate transformational approach to the way systems are designed, engineered, constructed, operated, maintained, and retired. The U.S. Department of Defense defines digital engineering as “an integrated digital approach that uses authoritative sources of system data and models as a continuum across disciplines to support lifecycle activities from concept through disposal.” Digital twin technology will include a safeguards analysis earlier in the design process, reducing the potential risk for diversion and misuse and proving the viability of a broader set of reactor technologies. The availability of these unique and comprehensive data streams opens the opportunity for a comprehensive understanding of all aspects of nuclear fuel-cycle facility operations to significantly strengthen nuclear safeguards and the nonproliferation regime in general. Such a tool will be a critical capability as the International Atomic Energy Agency currently safeguards over 200 reactors around the world and continues to operate on a zero-growth budget.

1 Introduction

Nonproliferation organizations must understand the potential proliferation pathways for “peaceful use” facilities to be a source of weaponizable nuclear material. The International Atomic Energy Agency (IAEA), specifically, must implement effective and efficient safeguards on nuclear fuel-cycle facilities to detect the diversion of declared nuclear material and misuse approaches to gain undeclared weaponizable nuclear material. To succeed in this critical endeavor, the physics, design features, and proliferation indicators must be understood, and the pathways mitigated. This requires a fundamental understanding of all aspects of an operating facility at the design level to conduct a diversion pathway analysis (DPA).

This is difficult for any entity that has limited technical resources and high staff turnover, such as the IAEA. Matching the technical know-how of a potential adversary is a very difficult challenge. Even for entities with robust resources, the ability to rapidly understand and manipulate a nuclear fuel-cycle facility to perform a DPA is challenging as new facilities are designed. Knowledge retention and overall capability in niche nuclear fuel cycle areas is always challenging, particularly if a country does not have such operational facilities to develop the next generation of experts, as is the case for the United States.

Nevertheless, modeling breakthroughs along with emerging technologies like Industry 4.0 (Industrial Internet of Things) data streams offer a unique opportunity to develop digital twins (DTs) to accurately perform a DPA and then monitor a facility. This in turn can allow for a safeguards-by-design approach to mitigate these pathways. This can mean not only applying existing technologies for that mitigation but also identifying technology gaps that need an research and development effort to address a pathway.

Digital engineering is defined by the U.S. Department of Defense as "an integrated digital approach that uses authoritative sources of system data and models as a continuum across disciplines to support life cycle activities from concept through disposal" [1]. A DT is the amalgamation of various digital objects (models, drawings, etc.) that are combined into an overarching framework that links all components [2]. DTs require a series of integrated models that can be dynamically updated to describe the product in question rather than static documents. To aid the product lifecycle, these designs are integrated across various platforms to ensure consistency and understanding throughout the design's lifetime (i.e., from conception to removal from service [3, 4]). DTs can accomplish these goals by utilizing concepts from digital engineering to develop a model encompassing a virtual design of a product, a physical design, or both [3]. Utilizing this information, we can create a virtual DT (i.e., a DT mimicking the behavior of a physical product through modeling and simulation) and a DT of a physical system (i.e., a DT containing both a physical asset and computational models representing that asset).

2 Digital Twins Used in Industry

DTs, and digital engineering in general, have already provided a wealth of benefits for other industries, including aerospace, manufacturing, and robotics [2, 5]. For the aerospace industry, DT technologies utilize simulations, replicate a continuous flight time history, and produce data to aid in determining upcoming maintenance requirements or other intrusions. These types of technologies allow integrating real data from the system (i.e., the aircraft) with modeling and simulation results to provide a robust analysis, which allows for the tracking of real-time degradation, anomalies, or disturbances. Focus areas include:

1. Structural monitoring—analyzes data of structural elements to assess fatigue and failure points and mechanisms [6–8]
2. Maintenance—combines recorded flight data with simulations to determine air-frame stresses to help determine when maintenance should be performed [9, 10]
3. Life prediction—assesses damages to determine lifetime predictions based on maintenance [11, 12].

In manufacturing, the focus of DTs has been to quantify and represent the complex nature of systems by examining human performance, external factors, and design constraint implementation. Similar to the aerospace industry, manufacturing utilizes a combination of real-world data and simulation models to help make accurate predictions on system performance and failures. Focus areas include:

1. Human-machine interaction—determination of human interaction points based on commonly used applications [13, 14]
2. Virtual factories—generation of a virtual factory to determine how a full system will perform before being built [15, 16].

DTs in robotics appears to be a relatively new field, with much of the focus being on virtual environments. Virtual commissioning and testbeds allow a virtual DT to help determine control algorithms for robots in the course development stage. This allows for an early prediction of failure points or design oversights before the development of a full-scale model. Our focus areas include:

1. Virtual commissioning—determines strategic plans, forecasting capabilities, and planning [17, 18]
2. Virtual test beds—examines the full technical system in its proposed operating environment [17, 18].

In the nuclear industry (outside of safeguards and security), researchers have begun to explore DT uses in operating, maintenance, and training. This work focuses on both currently operating plants and approaches for minimizing outages, failures, and downtime. Along with this, current work is looking towards the future and examining integrated systems for autonomous operations using live data and simulations to remotely control reactors. Focus areas include:

1. Training—provision of an extremely useful training surrogate for operations through reference plant simulators [19]
2. Condition monitoring—examination of online performance based on live data [20–22]
3. Autonomous operations—exploration of frameworks, sensors, and systems required for autonomous operations [23, 24]

Extending this emerging field to nuclear safeguards and security is ripe, as existing monitoring pathways already exist for current nuclear reactors. Along with this, building advanced reactors with safeguards-by-design approaches built into the reactor has the potential to reduce the risk and cost intrusion for operators.

3 Challenges for Safeguards and Security

3.1 Limited Funding Growth

Monitoring agencies, such as the IAEA, are projected to have little to no growth in funding resources over the coming decades [25]. Despite this, there is an expectation for nuclear growth through 2050, including more than 10 plants that came online between 2020 and 2022 [26]. As of 2021, there are 10 countries in the post-decision-making process (i.e., have begun construction on or signed contracts for pursuing nuclear) and 17 countries in the decision-making process [27]. Of the countries in the post-decision-making process, Bangladesh is building the Rooppur nuclear power plant (NPP), Turkey is building the Akkuyu NPP, and Egypt has issued a site license for a four-plant unit in El Dabaa, not to mention the facilities being planned in Jordan, Saudi Arabia, Poland, and Uzbekistan [27].

Combining the countries in the decision-making and post-decision-making process, the IAEA expects 10–12 nuclear newcomers by 2035 (increasing the current 32 countries by 30% and adding an estimated 26 GWe of nuclear power) [27]. Along with this, introducing microreactors (MRs) and small modular reactors (SMRs) could remove a significant barrier for countries to enter the nuclear realm [28]. Several countries already exploring SMRs are:

1. Argentina: CAREM (30 MWe pressurized-water reactor [PWR])—under development
2. China: ACP100 (125 MWe PWR)—under development; HTR-PM (210 MWe pebble-bed reactor [PBR])—startup testing
3. United States: NuScale (60–77 MWe PWR)—received design certification
4. Russia: RITM-200 (50 MWe PWR)—deployed in a floating power plant installation examining terrestrial applications
5. Canada: engaging multiple SMR vendors for siting.

The expected growth, and potential for much larger growth due to the deployment of SMRs, could provide an environment where the IAEA is underfunded and will be challenged to meed these new demands. To help overcome this challenge and limit the negative impacts on the IAEA, new technologies are constantly being explored. As one of those new technologies, DTs can provide a significant technological leap to assist and augment the IAEA's capabilities.

3.2 Small Module Reactor and Microreactor Deployment

SMRs and MRs could rapidly increase the number of states utilizing nuclear reactors for power and other applications, such as district heating. These reactors range between 1 and 300 MW and can utilization of multiple reactors; some plants may even have remote operators. Many reactor vendors are focusing on autonomous or nearly autonomous controls for MR and even SMR systems. The potential to heavily rely on instrumented systems provides an opportunity to leverage these systems for dual purposes.

While many SMRs and MRs are in the early or final design phases, some are in development. The deployment of tens to hundreds of smaller reactors and the lack of onsite operators is a fundamental paradigm shift for nuclear safeguards and security. Without a significant increase in funding for agencies like the IAEA, new technologies and measures will be required to monitor these operations.

4 Digital Twins in Nuclear Safeguards and Security

4.1 Digital Twins for Small Module Reactors and Microreactors

SMR and MR vendors are working to develop autonomous or semiautonomous reactors to reduce both operation and maintenance costs to encourage worldwide deployment. To ensure a robust operational envelope, autonomous controls will likely rely on heavily instrumented systems to provide constant and spatially dependent readings. The heavily instrumented systems provide an avenue to leverage the data that will already be streaming from the system to develop a DT with safeguards in mind.

Many MR concepts will be sealed before arrival, operated, and returned to the developer for refueling and other upgrades to create a more secure and proliferation-resistant concept [29, 30]. If an IAEA seal needs to be broken for maintenance for startup testing, a DT could provide the necessary confidence that the reactor is being operated under normal conditions. This type of DT could utilize aspects such as the control rod (or drum) configuration to verify the rate of fissile consumption; the removal or addition of a substance to the core would likely have a large effect due to the small core size. Utilizing DTs to monitor multiple MRs in series would then help provide an overall picture of the state's operations to determine if similar trends are occurring across multiple reactors. This information would allow for a comprehensive assessment to ensure proliferation was not occurring discretely over multiple reactors where an individual reactor may not be noticed. This particular adversary scenario is often described as protracted diversion, which can be accomplished through the slow removal of small quantities of fissionable material from a single facility or the rapid removal of small quantities from many facilities.

4.2 Integration with Safeguards and Security by Design

"Safety measures, nuclear security measures and arrangements for the State system of accounting for, and control of, nuclear material for a nuclear power plant shall be designed and implemented in an integrated manner so that they do not compromise one another." [31]

For reactor designs in the basic or final design phase, a virtual DT could be developed and utilized for both the nuclear components of the reactor (i.e., assessing nuclear safeguards) and for the NPP (i.e., assessing nuclear security). The first aspect for a virtual DT would be ensuring the design supports the infrastructure necessary for safeguards and security instrumentation. In reality, this would ensure that appropriate, and agreed upon, sensors were positioned in the core and around the facility to ensure a continuity of knowledge during operations. Closely tied with this would be the ability for unmonitored facilities to detect diversion and ensure appropriate measures were in place to detect these instances quickly and accurately. The virtual DT could interface with the IAEA to help determine vulnerabilities early in the design phase to prevent costly retrofits [31].

Besides applications for international safeguards as monitored by the IAEA, once a design has been chosen, a separate virtual DT could be designed for a combined domestic safeguards and security system with the physical asset to provide an interface between operations and safeguards and security. Once operating, each DT would assist and augment both an international and domestics safeguards inspector's ability to perform a site visit by determining inconsistencies that might need to be verified. The same would be true for domestic security inspectors to ensure a facility remains in compliance with their security posture. Besides assistance during inspections, the DT can provide near real-time monitoring for international safeguards and domestic safeguards and security inspectors and alert the responsible organization when off-normal events are detected. The key for security is understanding the security posture to respond to ongoing events, including, for example, distinguishing between a potential adversaries' diversionary actions and intended target and how to position a response force to defeat any adversary attempts. This understanding will be of paramount importance as some consideration is being given to utilizing an offsite physical security force for small autonomous reactors. Previous work with the IAEA would manifest itself in the ideal placement of combined sensors for both safe operations (beneficial to the operating state) and monitoring for nuclear safeguards (beneficial for the IAEA) [32,33]. In this sense, a DT has the potential to integrate nuclear safety, security, and safeguards (often described as 3S by design) [34, 35].

4.3 Preliminary Efforts at Idaho National Laboratory

Idaho National Laboratory (INL) has been championing the use of DTs in the nuclear industry for the past 3–5 years. This work has entailed developing a virtual DT to assess potential reactor misuses and diversion scenarios for sodium fast reactors and high-temperature PBRs [36]. For sodium fast reactors, access to control rod data and a selection of assembly power data provided enough information to accurately predict if the diversion or misuse of a significant quantity was occurring within a 1 year time frame [37]. For PBRs, the gamma analysis of a subset of discharged pebbles provided enough data for a statistical analysis of diversion scenarios [38].

The initial virtual DT created a framework that was easily applied to an operating nuclear research reactor: the AGN-201 reactor [39]. This work has been developing and exploring the challenges with incorporating a live asset into a DT. Current work is beig perofrmed to determine what levels of off-normal conditions can be detected using the DT.

Along with work in nuclear safeguards, researchers have been exploring utilizing next-level sensors and how these can be split to send data direct to a monitoring agency and the plant [23]. Research on industrial control systems could allow for this type of framework, where both the reactor operator and IAEA could receive independent streams of information. While this work is not directly safeguards related, it helps flush out many of the details associated with monitoring and using sensors for SMR and MR systems.

Another DT application being developed is for aqueous metal separations. INL is participating in in the development of a DT that replicates an aqueous separation utilizing centrifugal contactors. The resulting DT will aid in monitoring, model implementation, and safeguarding separations equipment and processes. Preliminary DT development is taking place at INL's Solvent Extraction Laboratory, where two teams are focused in parallel on DT development: one integrating traditional sensors (e.g., optical sensors) and the other integrating nontraditional sensors (e.g., acoustic sensors). To achieve the goal of having a functioning DT, the various components are integrated into a unified system through the development of adapters that connect a central data warehouse (i.e., DeepLynx) to the various project nodes (e.g., LabView data streams, machine learning (ML) models, chemical models, international safeguards support, and visualizations). The cumulative results of this work are an improved understanding of sensor integration and analysis techniques and several modular components that can be modified and specialized for alternative applications. Beyond that, these projects are helping provide a framework for data-driven assessments that can be leveraged in developing and monitoring future aqueous metal separations assets.

4.4 Challenges in Implementing Digital Twins

Though the potential benefits of DT technologies are vast and encompass much of the international safeguards and security of nuclear reactors, there are additional aspects and challenges to consider when implementing a DT. Some of the challenges posed by using any digital product (DT, artificial intelligence [AI], and ML in this case) in a potentially high-risk application include [3, 4, 30, 33]:

1. Lacking regulatory guidance and requirements for compliance and acceptance
2. Lacking international standards for design (including cybersecurity) of DTs, AI, and ML
3. Ensuring a workforce with the necessary skillsets to design, test, implement, maintain, and upgrade, as necessary
4. Performing the proper verification and validation of its performance over the facility lifecycle
5. Assuring user trust through explainability and periodic performance testing.

5 Conclusion

DT technology has successfully been deployed by other industries to enhance their abilities to monitor, perform maintenance, and virtually explore conditions that are expected to occur in a real-life reactor. These applications leverage both the virtual and physical space to help detect anomalies, track the system response with respect to time, perform predictive maintenance, and predict how the system will respond to various events. Nuclear safeguards and security face many of the same challenges: determining if changes in reactor operations or material movement require further investigation, monitoring a system over time for system quantification, and attempting to predict weak areas in current safeguards or security assessments, addressing both physical and cyber threats.

DTs provide an avenue to augment the current abilities of the IAEA and domestic safeguards and security programs. Combining DTs with AI technologies can lead to new innovations in process monitoring detection, specifically in event classification and data tampering. These innovations can be furthered through the online monitoring of facilities to determine if reactors are operating nominally or requiring additional inspection. DTs could also help bring safeguards analysis earlier in the design process, reducing risk to the reactor design, avoiding retrofits, and proving the viability for a broader set of reactor technologies. The availability of these unique and comprehensive data streams opens the opportunity for comprehensive understanding of aspects of nuclear fuel-cycle facility operations to significantly strengthen nuclear safeguards, the nonproliferation regime in general, and domestic safeguards and security.

Many groups throughout the world are attempting to provide tools and systems to aid in ensuring nuclear material is being used in a peaceful manner. Given the IAEA's zero-growth projected budget, and the potential for hundreds of new nuclear reactors being started up, it will be imperative to explore all technologies that could alleviate some of the workload expected of IAEA and domestic inspector and physical security response forces.

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