Evolution of technologies for the Future: Remote Detection Advancements for Nuclear Material Management.

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ABSTRACT

The National Nuclear Security Administration (DOE/NNSA) Office of Defense Nuclear Nonproliferation Research and Development (DNN R&D) has a vision for developing technology that will provide unobtrusive surveillance with instantaneous accountability regarding the monitoring of nuclear material and nuclear material plant operations. Monitoring and characterization of nuclear facilities is an essential activity to meet the goals of the nuclear nonproliferation community. New developments in machine learning and cognitive inferencing have potential to greatly assist in delivering real-time monitoring capabilities and help in optimizing plant operations. Operating such automated monitoring systems requires good knowledge management, ability to dynamically update information, quantification of uncertainty in measurements, and superior quality interpretation of machine learning and artificial intelligence algorithm outputs. This paper will introduce basic concepts regarding how research teams have been able to establish analytical techniques that couple observations of diverse physical phenomena with subject matter experts (SME) knowledge that will inform data collection and how to draw meaningful conclusions about nuclear activities.

INTRODUCTION

There exists a desire to obtain a state of persistent monitoring of special nuclear material and related materials in nuclear related operations. The vision being unobtrusive surveillance with instantaneous accountability. Full persistence is often an unobtainable goal, as constant monitoring is attended by high cost in an already expensive endeavor.[1,2] In an effort to improve persistence capabilities DNN R&D has invested in a set of technologies that can demonstrate the concept of dynamic persistence.

Many tell-tale signs of nuclear proliferation activities are subtle, fleeting, and rare.[3] One must assume that detection of these signatures require measuring everything, everywhere, all the time. Finite resources, however, restrict the art-of-the-possible. NNSA scientists developed a concept to demonstrate a capability to measure the right thing, in the right place, at the right time in the context of nuclear proliferation activities.

Dynamic persistence is attained through a comprehensive sensing capability that incorporates detailed knowledge of process sequences, state of the art cognitive inferencing tools, and intelligent coordinated sensing concepts.[4] Design principles of the system include the ability to dynamically make the best use of available sensing assets and maintain a low barrier of entry for incorporating new collection assets. This paper will discuss the basic building blocks of the system known as Persistent Dynamic Nuclear Activity Monitoring via Intelligently Coordinated

Systems (Persistent DyNAMICS). The dynamic persistence construct provides the first steps towards mission-specific, comprehensive sensing systems to detect, locate, or characterize nuclear activities without fully persistent sensors.

BACKGROUND

The Persistent DyNAMICS work consists of multi-disciplinary efforts that developed and assessed the building blocks of the dynamic persistence construct. The primary elements that established the capability are: 1. Identification of SME-informed, linked sequences of observables, confirmed by measurements at a testbed, that have utility for remote confirmation or quantification of key nuclear processes, 2. Selection of a persistent suite of multi-modal remote sensors to collect observables and measure the temporal relationships between them, 3. Creation of an ecosystem for a dynamically persistent, intelligently coordinated sensors to autonomously monitor and detect observable sequences under realistic constraints, 4. Integration of the system elements into an intelligent, coordinated sensing architecture. At the end of FY23, Persistent DyNAMICS will be established as a proven, prototype capability for dynamic persistence, including a representative set of sequence signatures, physical assets, and required architecture elements. This will allow DNN R&D to evaluate the long-term impact of the dynamic persistence approach towards answering important questions to the nuclear nonproliferation problem set. Products from this effort are expected to have broad value to the DNN R&D mission portfolios that examine and follow special nuclear material production, weaponization, safeguards. Dynamic persistence provides a path towards mission-specific, cognitive sensing systems to characterize, confirm, or quantify nuclear activities without fully persistent sensors.

The Persistent DyNAMICS concept describes a new paradigm in proliferation detection within the remote sensing mission. It recognizes that the understanding of temporal relationships between observables can be used to improve recognition of both individual activities and the set of linked activities that generates key materials and components in commercial and state level nuclear material production. To successfully develop the scientific foundation and build the capability for dynamic persistence, the DOE/NNSA laboratory teams executed four primary tasks: Prediction, Data Collection, Intelligent Coordinated Sensing, and Integration.

The prediction task focused on making progress identifying linked sequences of observables with utility for remote confirmation, characterization, or quantification of key nuclear processes. The work was organized to advance understanding of sequence signatures and build the foundational knowledge for the predictive capabilities that are needed to achieve persistent dynamic sensing. The prediction task provided the foundational predictive elements of the dynamic persistence sensing system and provides stewardship of this knowledge as it evolves over time.

Data collections task were focused on selecting and employ a persistent suite of remote sensors to collect observables and measure the temporal relationships between them. Data from this task will be used to recognize and discover linked sequences, to assess the impact of emerging persistent capabilities, and to inform development of and provide a performance benchmark for dynamically persistent sensing. The work was organized to make remote sensing observations of a selected testbed and provide the foundational distributed sensing elements needed to achieve dynamic persistence. The data collection task provided the foundational sensing elements of the dynamic persistence sensing system.

Coordination work focused on creating a dynamically persistent, intelligently coordinated sensor ecosystem to autonomously monitor and detect observable sequences under the constraints of realistic persistence. This work will develop the building blocks of an intelligent coordinated sensing capability to bring together diverse remote sensing capabilities to make multi-phenomenology sensing collections in real-time. Critical sub-tasks will include a scoping phase to design an end-to-end dynamic persistence architecture, the development of foundational dynamic sensing infrastructure. This task provided the foundational coordinating elements of the dynamic persistence sensing system. Coordination tasking developed and implemented tools to allow dynamic persistence to be realized in the Sensor Ecosystem. As such, Coordination interfaced with critical subsystems in both the definition and implementation of the ecosystem. Coordination was realized through the use and development of state-of-the-art machine-learning and artificial-intelligence tools to support creation of the dynamic cognitive system that orchestrates Persistent-DyNAMICS. Coordination guided the system toward the detection of observable sequences generated by key subsystems, as well as to the recognition of unanticipated sequences through empirical observation. Succes required a close connection among the feedback mechanisms used by the cognitive infrastructure.

Integration tasks focused on unifying the data output from the previous elements into a functional system for intelligent, coordinated sensing. This takes a system-of-systems engineering approach to include all the systems engineering efforts for integrating individual components to a unified dynamic persistence sensing system.

Unification of these concepts has been achieved and developed into a prototype capability that implements the principle of dynamic persistent monitoring and provides a path towards mission-specific, cognitive sensing systems to characterize, confirm, or quantify nuclear activities without fully persistent sensors.

BASIC CONCEPT

The Persistent-DyNAMICS concept moves beyond the current Internet-of-Things with cloud-based computers to an innovative approach, called Edge computing, where the complex sensor data are analyzed near the sensors (“pushed to the edges”)[5]. Edge computing’s advantage is the ability to reduce and abstract data where it is generated, instead of pushing huge data volumes to the cloud for analysis. For autonomous remote sensing ecosystems, Edge computing allows faster real-time analysis, inclusion of complex data-intensive sensors in the ecosystem, and more efficient real-time follow-up.

The Artificial Intelligence Technique employed for engineering the cognitive component of the collection coordination is called Case-Based Reasoning (CBR) with Learning.[6] CBR is a well-established AI technique that was inspired by human reasoning and learning. Individuals solve problems by applying previous experience (individualized or learned) as adapted to the current situation. The life cycle of CBR has four main steps: retrieve, reuse, revise and retain. In the Persistent DyNAMICS application of CBR, after each event-of-interest is identified and classified, the event is mapped to a case containing the expected sequence signature and a follow-up execution plan which describes what measurements need to be made and when they need to be made to collect the key signature information. Persistent DyNAMICS generated each event-of-interest based on: (1) historical successful responses and (2) sequence signatures predicted through select algorithms. The CBR system learns by evaluating the quality of the response after each executed coalition and saves successful responses as new cases. This provides a natural way for the system to bootstrap and to learn from experience, even when the signature sequences are poorly understood. Persistent DyNAMICS uses two approaches that compensate for the unique data environment by incorporating foundational knowledge into model-based inference tools. The supervised machine learning (SML) approach generates synthetic training data using simulators informed by the forward models, then applies standard machine learning techniques to perform inferences on real data (the inverse model). The dynamic Bayesian network (DBN) approach combines the forward and inverse models by encoding foundational knowledge as a set of variables and their conditional dependencies across time.[7]

The Persistent DyNAMICS design allows construction of systems-of-systems or ecosystems that optimally respond in real time to emerging threats or unexpected collection opportunities by joining an ultra-fast hard-wired follow-up response with a dynamic cognitive response. The cognitive response employs temporary coalitions drawn from a diverse set of sensor technologies that span ground, air, and space domains. The goal of the Persistent DyNAMICS cognitive response is to optimize autonomous-remote-sensing collection for an event-of-interest that is shaped by the nature of the event. Each new event-of-interest is spawned as a potential coalition and is distributed by a coalition manager (event broker) in real time to a collection of external agents with an invitation to join the coalition. The coalition manager collects coalition members and determines before the expiration of an opportunity window if sufficient interest is present to merit an organized coalition follow-up. If not, the potential coalition is stopped and agents that expressed interest are notified. But if sufficient interest is present, the start of the coalition is announced, and participating agents are assigned roles that reflect their capabilities. The ability of a sensor to opt in or opt out of the event coalition in real time based on the nature of the event is an innovative aspect of the network prototype that allows the owners of sensor to accomplish their primary mission goals on an as needed basis.

EXAMPLE

Persistent DyNAMICS was first evaluated at Oak Ridge National Laboratory's High Flux Isotope Reactor (HFIR) and the Radiochemical Engineering Development Center (REDC). HFIR/REDC provided the opportunity to determine whether the system could successfully monitor nuclear material operations such as the irradiation and chemical separation of targets. In this case the goal was to see if reactor activities were consistent with short-lived medical isotope production of molybdenum (^{99}Mo) or some other proliferation-relevant isotope. Due to its short half-life, production of ^{99}Mo has specific timetables for production that include limited cooling, production, and packaging. The task of the remote sensing network was to determine if and how difficult it is to distinguish this activity from the myriad of other ongoing activities at the site. The Persistent DyNAMICS team deployed the advanced sensor network and included visible imaging, thermal imaging, electromagnetic and radiofrequency, vibration sensing, acoustic sensing, and overhead collections as nodes in the feeding data to the cognitive inferencing engine.

Processes begin in an equivalent manner with targets being delivered to the site. If one is producing material for a radioisotope thermal generator, for example, the neptunium (^{237}Np) target will be irradiated in the HFIR for ~70 days and then be removed to the cooling pool for a period of months. If a target is being processed for ^{99}Mo the HEU target may only be irradiated for approximately a week and cooled for about a day to ensure rapid processing and delivery of the medical isotope to appropriate medical facilities.

The Persistent DyNAMICS network collected data over several HFIR cycles to help establish a meaningful background and then collected data over more HFIR cycles to evaluate the system inferencing procedures. The system follows the methodology developed previously in our office called the Modeling and Inference for Remote Sensing (MIRS). The MIRS approach to activity characterization from simulated time-sequence observables is to rigorously specify the hypotheses as material flow models. The computational model is needed to simulate the hypothesized activity to compute parameters for the model, validate it, and provide a baseline distribution of the likelihoods computed in the next step. Once a model is trained, known inference algorithms are used to compute the relative likelihood that each model explains the sequence of remote sensing observations. The model with the highest likelihood corresponds to the answer to the questions posed. In this way, modeling and inference links information across facilities, observables, and sources of data, assisting the analyst by finding patterns across multiple sensors and over time that are consistent with models of facilities that have been verified. Analysts do not need to know what pattern to look for in advance, although SMEs do need to identify useful observables and the sensors that can detect them.

In our test case the system was able to successfully determine whether HFIR was operating or not, producing ^{99}Mo, or some other proliferation relevant isotope. The system can rapidly and autonomously analyze multi-modal, disparate data, and synthesize it to yield the of the state of the plant, the expected activity, and assign probability of confidence to activity. Over the course of the test period activity, the reactor state inferences achieved over 95% F1-Score in a weighted average over the three classes, and the hypothesis inferences were correct in determining the nature of the isotope production occurring.[8] In addition to the original deployment at HFIR, the Persistent DyNAMICS network has been successfully tested at other sites and is planned to be used at NNSA testbeds to further evaluate the effectiveness of the system under varying mission parameters.

CONCLUSIONS

The Persistent DyNAMICS team has brought the vision of designing, building, and demonstrating an architecture for dynamically persistent monitoring of nuclear processes through intelligently coordinated sensing to reality. This body of work brought together experts in nuclear materials, machine learning, data science, safeguards, and weaponization detection. Transferability and extensibility of the prototype has been demonstrated at various testbeds in addition to the example mentioned herein. The prototype technologies developed for this project are general and have the potential to be tailored for wide use across the nonproliferation mission space. The Persistent DyNAMICS team has innovated to create novel solutions and approaches to a suite of nuclear security challenges, collaborated with a range of partners to maximize impact and bolster mission success, and delivered a unique autonomous network to address evolving issues in the nuclear security environment.[9]

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