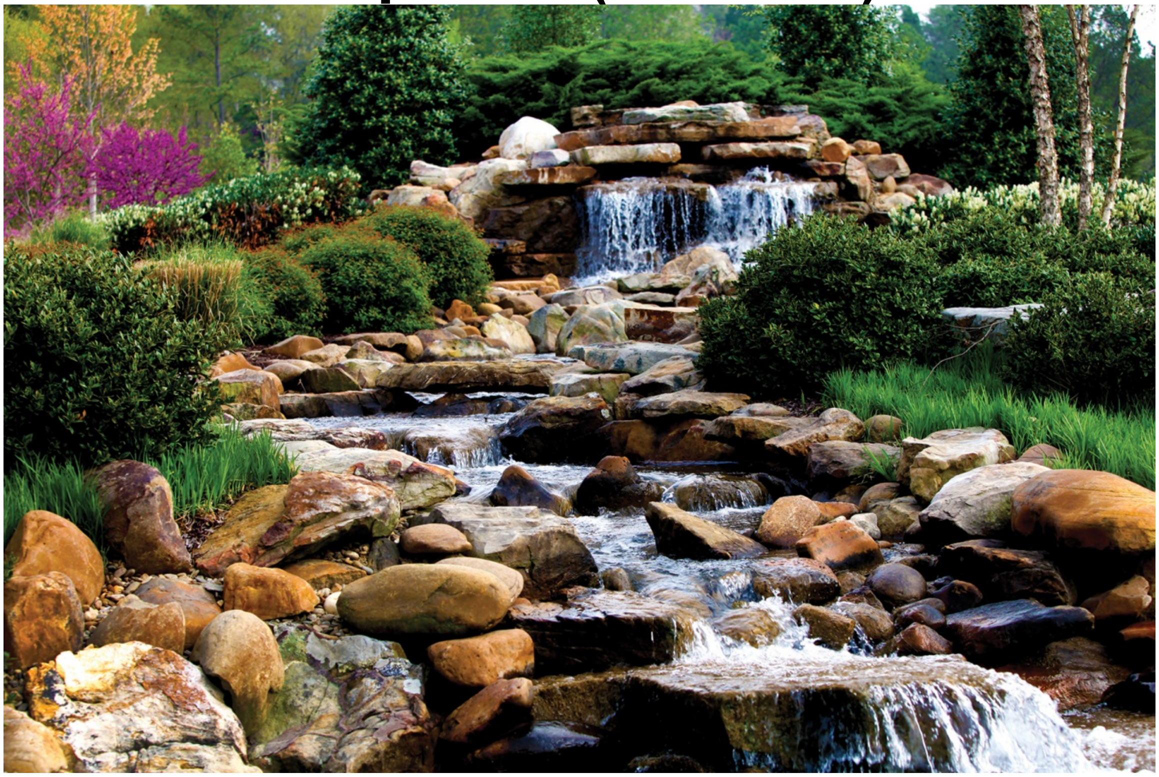
ORNL/SPR-2022/2639

Smart Packaging for Critical Energy Shipment (SPaCES)



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September 2022

Oak Ridge National Laboratory

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ABSTRACT

Recent technical advances have brought forth revolutionary Smart Packaging (SP) technology. SP incorporates multiple electronics, chemical, and mechanical sensing technologies into packaging materials, and utilizes them to monitor and display package content status. SP can also employ embedded micro actuators to react to undesirable package conditions such as moisture/temperature anomalies or harmful chemical reactions and neutralize it. When further integrated with wireless sensing and secure networking, SP provides wholistic system-wide remote situation awareness capability for real-time crisis management. Finally, we also see that SP can be further integrated with 3D printing technology to offer form-factor customization and application specific solutions suitable for DOE (Department of Energy) NNSA's (National Nuclear Security Administration) R/N (radiological/nuclear) material shipment and management needs; this has the potential to improve safety, security, and overall operation process quality.

This report surveys SP technology as the state of the art (SOTA) and analyzes how it can integrate with cybersecurity and 3D printing to address NNSA's critical R/N material shipment and storage requirements. This report further presents our FY23/24 investigation plan describing project background, goal, motivation, proposed work, and statement of work and cost.

1. MOTIVATTION

The vision of this Smart Packaging (SP) technology effort is to equip each R/N cargo/package in transport with an edge computing device and a suite of sensors for sensitive material real time tracking and monitoring. The communication from packages' sensors to wirelessly connected edge devices and eventually up to the cloud via telematics units enables system-wide remote monitoring and situation awareness for R/N cargo transport monitoring and storage management. This SP-enabled approach enhances R/N cargo transport security and safety. The SP in context goes beyond simple smart tagging. It can leverage additive manufacturing technology to integrate sensors and edge devices into 3D-printed cargo containers. We will examine DOE specific requirements and prototype appropriate SP utilization for DOE R/N management scenarios.

2. BACKGROUND

Smart packaging (SP) is paving the way to a new era for many consumer-product industries. For example, product packaging embedded with intelligent sensors and actuators is becoming increasingly common, particularly in food and pharmaceutical industries. For example, Coors Brewing Company releases "Cold Activated" bottled beverages with labels printed using thermochromic inks that turn the white lettering and the Rocky Mountain icon blue when the bottle reaches the optimal drinking temperature. This SP application takes the guesswork out of when is the best moment to enjoy the beer. On the other extreme, there are also SP implementations which can instantly heat beverages (e.g., coffee) on-demand using exothermic chemical reaction between water and hygroscopic salt around the beverage cups within the packages. For food packaging, SP can detect spoilage by sensing food chemical composition alteration, and then release active agents to control the deterioration to maintain freshness.

Potential SP applications are growing rapidly across multiple industries. It is commonly observed that SP interacts directly with package content and can sense its status for display, as in the case of the cold Coors beer. Additionally, it could also act on the package contents via actuation of chemical or biological responses to control the package conditions. These conditions could range from temperature, as in the case of the hot coffee, to quality control, shelf-life extension, or inhibition of certain chemical processes or microbial/fungal growth.

Furthermore, when sensors are network-enabled and scanned by RFID readers or monitored wirelessly, SP can report package status to remote monitoring stations. Conversely, SP can also receive remote commands to actuate certain active responses in control of package conditions.

Most of today's SP development orients toward the consumer-product section. While it is not developed targeting DOE R/N transport/management needs, the technology shares many common functionalities such as sensitive cargo content monitoring and tracking, status display and remote emergency awareness and control. Another analogy is pharmaceutical SP applications that call for traceability and integrity monitoring for the medication. We see a good potential that, when coupled with appropriate technologies (e.g., radioactivity sensing, 3D printing, cybersecurity) SP can play a significant role in assisting NNSA to address mission challenges for secure R/N materials transport, storage, and broad management issues.

This report documents:

1. High level state-of-the-art (SOTA) SP technology survey
2. Pertinent technology components (sensing technology, 3D printing)
3. Architecture and prototype design
4. Potential DOE NNSA SP scenarios & cybersecurity
5. FY23/24 planning

3. HIGH LEVEL SMART PACKAGING TECHNOLOGY STATE-OF-THE-ART SURVEY

SP has emerged as an active management technology to track, react, and improve logistical efficiency across many industries by utilizing packaging as a connected and available platform. It can be used to monitor movement of cargo, analyze environmental conditions, ensure quality, and improve safety and security. Schaefer and Cheung [1] extrapolate that smart packaging is an umbrella term encompassing two forms of packaging: active packaging and intelligent packaging.

- *Active packaging* is packaging which contains embedded components that aid in the preservation of quality and material in the packaged products. Active packaging does not necessarily contain electronic devices. It is often used in the food and perishables industry, as packaging can be manufactured with components such as odor eliminators, oxygen scavengers, or humidity controls. This type of packaging does not have the ability to communicate or report information about the packaged product.
- *Intelligent packaging* is packaging which contains sensors or embedded components, particularly electronics, which monitor and report the conditions of a product or environment. Intelligent packaging is also often found in the food and perishable industries.

It offers the ability to remotely collect data from products such as location, temperature, gas concentration, and more. This type of packaging does not have the ability to act or react based on the information it gathers—it is a passive reporting tool.

As the marriage of active and intelligent packaging, SP becomes an attractive solution for enumerating, securing, monitoring, and reacting for an incredible number of industries. This field is still relatively immature, and to our knowledge, there has not been an approach to nuclear transport security that includes this type of embedded monitoring.

SP can involve RFID tags, wireless sensors, and further network-capable embedded edge-computing IoT (Internet of Things) devices in its operation. With that, comprehensive product information can be made accessible online instantly. This information can include individual and specific package status, its history, and any additional transient information such as on-going product promotions can also be perused on the spot. Overall, networked SP enables powerful remote situational awareness and distributed security/safety monitoring.

Potential SP scenarios are growing widely in many application domains [2]. The following sections give an illustration of some areas being developed. The most established is by far the retail consumer product industry, particularly in food retailing and merchandise packaging. It is also worthwhile to note that, with the increasing adoption of IoT/edge-computing devices, SP applications are growing rapidly and with even deeper penetration into numerous aspects of social life.

<u>Food and drug retailing</u>

This is by far the most progressive SP application area with many well-developed applications [3]. Food chemical compound change sensing (via active agent detection, as illustrated in Figure-1), or detection of changes in moisture, temperature, or bacteria/fungus growth sensing, expiration dating, etc. are all indicating parameters in food SP sensing.

Figure-1 Food SP active agents chemical compound transition sensing [4][5]

From the business point of view, food SP simplifies inventory management with improved quality/safety control. From the consumers' perspective, SP offers instant food safety and nutrition information for the specific packages, on spot, for inspection. Figure-2 illustrates that, beyond the traditional packaging, SP offers extra benefits in protection/preservation, containment, communication/marketing, and further convenience functionalities.

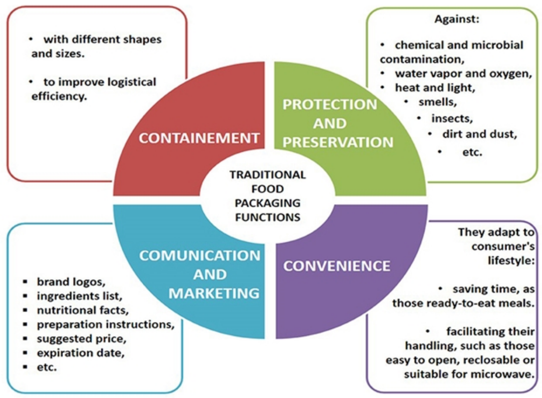

Figure-2 Additional functions of food SP [6]

Pharmaceutic SP is another relatively progressive area. Smart medication SP labels can monitor or record medication temperature during transportation and storage, thus provide integrity and safety assurance. Pharmaceutic SP NFC tags can also provide patients with critical information such as potential allergy warning when using the medication. Smart labels can also record patient prescription intake. SP further simplifies pharmaceutical manufacturer's inventory management and stocking control and helps in data collection for clinical trials.

Figure-3 Benefits and prototype blister package of pharmaceutical SP [5][7]

<u>Operation and logistics management</u>

SP helps to improve large and complex logistics management and business operations such as manufacturing. Take the example of modern commercial airplane manufacturing. The logistics of sourcing/transporting/storing large number of parts globally, coupled with a sizable just-in-time, globally distributed manufacturing process for putting numerous components together, all in sync but in different phases, is an extremely complex undertaking. SP-enabled distributed remote sensing/monitoring can significantly bring down the management complexity with detailed visibility and controllability. Total quality control is improved via data analytics on SP-enabled information collection. Additional logistics and operation management scenarios could also include:

- Complex supply chain management, such as ETA (estimated time of arrival) updates or flow analysis and prediction
- Distributed and large-scale sensitive material monitoring/management (e.g., R/N materials)
- Short-landed/over-landed containers, containers left behind on pier/warehouse or rolled off, unexpected or wrongly discharged containers (Figure-4)
- Fragile, breakable, or dry cargo shock/temperature monitoring & recording
- Container daily status messaging for fleet management
- Inter-modal transition, depot reconciliation

Figure-4 Operational and logistics SP [8][9]

Authenticity and security awareness

Security and integrity are critical. SP assists in identifying security-pertinent logistics anomalies such as unexpected opening of the package or unanticipated temperature changes—for temperature sensitive cargo—that could lead to potential compromise of package content quality or authenticity. This can also aid in identifying anomalies such as empty gate-in/gate-out at depot, trip deviation, or unusual vibration/shocks that could lead to damaged or lost packages.

Compliance and quality control

When there is a requirement to enforce critical laws and regulations, compliance checking and enforcement become a challenge. Export control or border crossings often require compliance or custom inspections. SP can be e-verifiable and provide a clear manifest for clearance purposes. On the business side, SP helps to validate requirements such as contract-compliance container routing, reefer pre-trip inspection, or port infrastructure usage monitoring from the port authorities. Furthermore, in all such circumstances, SP can potentially be integrated as part of the total system for automated compliance verification and quality assurance.

Figure-5 SP for border-crossing compliance checking [10]

4. PERTINENT SENSING TECHNOLOGIES AND ADDITIVE MANUFACTURING

Sensing technologies

The application of SP technologies in R/N material management introduces several opportunities to explore additional emerging technologies. The goal of SP is to secure, track, monitor, and react to changes in environment, situations, or state. Thus, the inclusion of numerous embedded sensors would allow a security operations center to remotely monitor the status of the cargo. Sensors could be changed or customized depending on the application and information desired. In our initial investigation, we are pursuing the following options:

- *Radiation sensor(s)*: Sensors that can communicate readings (such as embedded dosimeters) could indicate abnormalities in radiation readings in both the environment and the package. This type of information could be critical in the event of a vehicle accident or improper handling/storage of materials.
- *Thermal camera(s)*: Small cameras that could be embedded into SP and monitor, record, or transmit interval pictures. These cameras display heat sources and could alert if the package is being tampered with, relocated, or in concerning environmental conditions.
- *GPS sensor(s):* Small GPS units can be embedded in SP that report cargo location. These units will report cargo location during transport and could allow for easy verification of proper movement.
- *Light sensor(s):* Small sensors can react to the presence of light. These sensors could indicate if the package has been removed from an enclosed trailer, as well as alert if the container is being tampered.

Ideally, these sensors would be obscured and obfuscated from an adversary or uninformed parties. To accomplish this goal, our team is exploring mounting options. One leading candidate is the ability to additively manufacture, or 3D-print components of a B-type container, such as an impact zone, which would maintain package stability and performance. Cavities would be inserted during the printing process where our sensors and microcontrollers would be inserted.

Additive manufacturing

ORNL's Manufacturing Demonstration Facility (MDF) is a research leader in state-of-the-art additive manufacturing implementations. The MDF has been involved in past research and development in exploring material properties for the safe transportation of radiological sources. Further, recent technology such as the MedUSA multi-arm robotic printer has allowed for the large-scale manufacturing of metals such as titanium, which have attractive properties such as impact and heat resistance. Research has also been performed to create helium-leak-free 3D-printed titanium-based containers. Thus, there are attractive options within MDF for creating a subsection of a B-type container with cavities to obfuscate sensors.

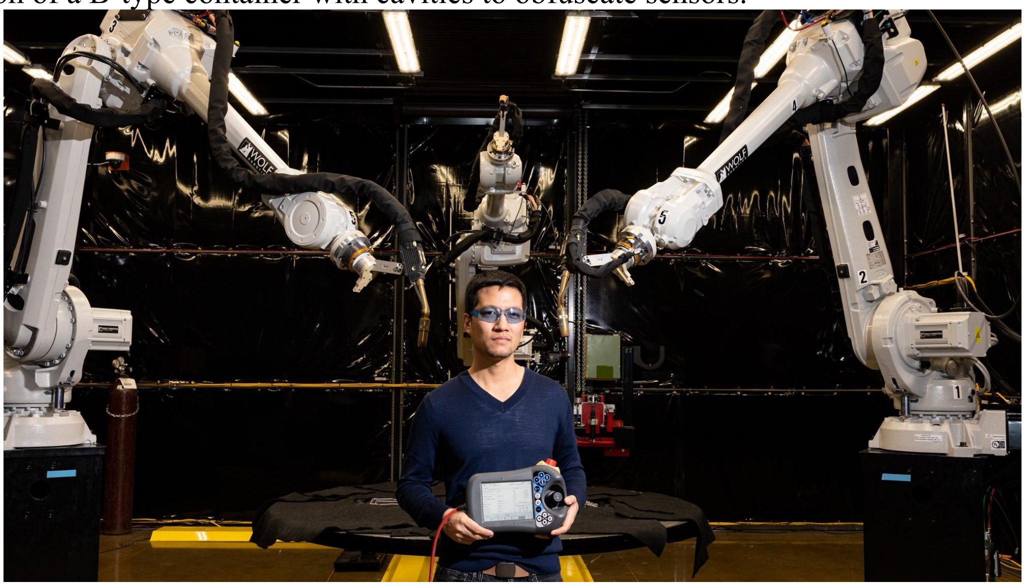

Figure-6 ORNL engineer Peter Wang, pictured with MedUSA 3D Printer.

One risk for this effort is cost. This will be one of the largest single-print, safety-critical, titanium-based manufacturing prototypes. The initial planning and design phase will occur in FY23, which will allow for accurate estimation of this cost. For instance, the overall size, thickness of materials, thickness of layers, and surface finishing will have a large impact to the requested budget.

5. ARCHITECTURE AND PROTOTYPE DESIGN

The architecture for our application of SP to R/N material transportation involves many small, low powered embedded microcontrollers which are connected to one or more co-located sensors. Each microcontroller will communicate using a wireless protocol to relay their sensor information to a head node. The head node will be a larger embedded computer which categorizes and reports the information to a central telematics unit. In our design, we will report this information to ORNL's T-STAR [11] device. We are exploring numerous embedded computers, microcontrollers, and wireless network protocols for security, power requirements, maintainability, and operational challenges. Ideally, we like to see sensors obfuscated from an adversary. However, if frequent, high power wireless communication reveals the presence of sensors, limited obscurity can still be achieved via employing passive sensors that respond only when scanned. Another approach would be to utilize remote-powered sensors or built-in integral data communication channels to reduce RF power consumption and profile.

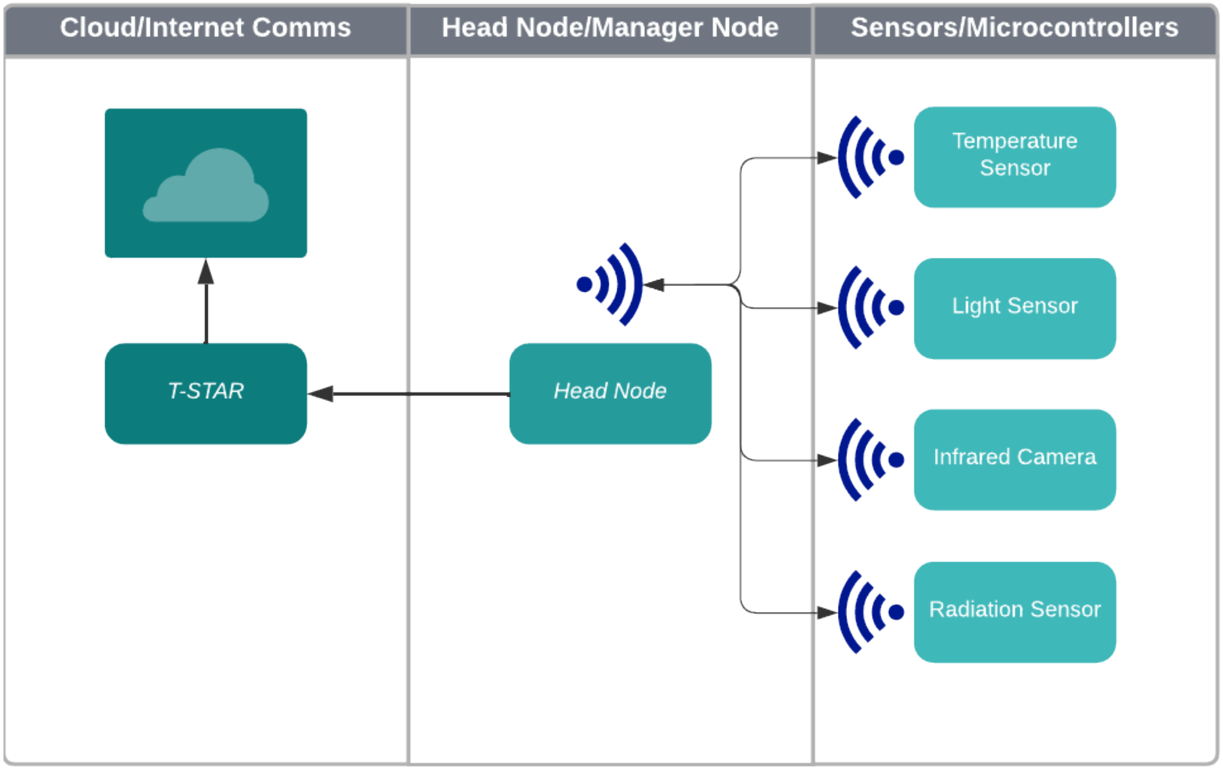

Figure-7 High-level diagram of SPaCES architecture depicted.

Embedded microcontrollers

ESP32: A cost-efficient and low-powered embedded microcontroller platform, ESP32 devices are ubiquitous in IoT products and can operate in low-power environments. These items have been identified as potential candidates for deployment in the SPaCES prototype.

Teensy4.0: A popular, commercially available development board which features a powerful processor and large amount of memory. These devices are more standardized than ESP32-based microcontrollers—as they are designed by only one manufacturer—and are an alternate candidate for deployment.

Embedded computers

Nvidia Jetson AGX Orin: A powerful embedded supercomputer which includes GPU acceleration and 32GB RAM. This device is built to explore artificial intelligence applications in embedded systems. This would serve as the head node in our prototype, and a platform to explore future data science opportunities within the mission space.

Recompute J1010 Edge AI Device: This embedded artificial intelligence device is based on the Nvidia Jetson Nano platform. Like the Nvidia Jetson AGX Orin, this device is meant to power machine-learning and data science applications in embedded applications. However, the Jetson Nano is not as powerful—with only 4GB RAM comparably. This device is being explored as a lower-cost alternative to the more expensive Jetson AGX Orin.

Raspberry Pi 4: A cheap and power-efficient embedded computer. The Raspberry Pi 4 includes 8GB RAM and 40 accessible pins for power and general-purpose input/output (GPIO). Raspberry Pis contains a full Linux environment and will allow us to rapidly prototype the required technologies prior to deployment.

Wireless protocols

LoRaWAN: Long Range Wide Area Network (LoRaWAN) is a communications platform that allows for low-powered devices to operate over large distances with low transfer speeds. This protocol is designed with energy efficiency in mind, which is an important consideration for sensors that require long-term installation with minimum service and maintenance. LoRaWAN allows for connectivity up to 6 miles away and operates between 902-928MHz in the United States. This allows for connectivity through long distances and dense material, such as buildings and tunnels.

Zigbee: Zigbee is a standardized wireless platform for low-power low-bandwidth applications, such as medical devices, traffic management systems, and other industrial equipment which requires short-range transmission. This protocol is used for close-proximity, secure communications. While it can be installed as a wide-area mesh, our low-power application will be limited to 10-100 meters, depending on environmental conditions.

Thread: Thread is a more recent alternative in wireless communication protocols but has seen remarkable growth and maturity given its governing by the Thread Group alliance, which includes industry partners such as Google and Apple. This protocol offers IPV6 addressable nodes, the ability to implement AES encryption, and cloud connectivity without the need of proprietary routers. Thread broadcasts at 2.4GHz, using IEEE 802.15.4 radio technology. The total broadcast distance is the most limited of the three explored protocols, transmitting between 20-30 meters.

Prototype and testbed

Prototyping SP implementations will begin with the construction of a testbed. This testbed will allow us to initially configure devices, develop software, and explore the security posture of off the shelf hardware. It will exist as a bench-top server-racked drawer which can be accessed remotely and easily relocated for experimentation. This environment will serve as the primary step in building the tools, software, and hardware pieces needed to totally integrate the system. Once an experimental proof of concept is established, the initial prototype will be developed for validation in-lab and in relevant environments. This prototype will be deployed at ORNL's Global Evaluation, Analysis, Research, and Security (GEARS) facility using a preexisting type-B container. After our prototype design is validated and demonstrated in a relevant environment, we will evaluate operational environments. These evaluations include performance requirements of type-B containers, and initial tests with ORNL's MDF for suitable material and designs for additive manufacturing. The final prototype will exist as a 3D-printed type-b container with embedded smart packaging technology. This construction could then be evaluated for safety, performance, and security as a package.

6. POTENTIAL NNSA SP SCENARIOS & CYBERSECURITY

National Nuclear Security Administration (NNSA) within DOE is chartered with the mission of safeguarding US national nuclear security. NNSA manages the safety, security, and effectiveness of the US nuclear weapons stockpile and provides the US Navy with safe and effective nuclear propulsion. NNSA also works to reduce global nuclear weapons threats (with multitude of nonproliferation, R/N material removal, and counter-terrorism programs) and to respond to nuclear and radiological emergencies in US and globally.

Within NNSA, the Global Threat Reduction Initiative (GTRI) focuses on reducing and protecting vulnerable nuclear and radiological material located at non-government sites all over the world. This effort supports DOE nuclear security priority by preventing access to R/N materials by terrorist organizations. This initiative consists of three efforts: Convert, Remove, and Protect.

- The *Convert* effort concentrates on activities such as converting civilian research reactors from using HEU (Highly Enriched Uranium) to LEU (Low Enriched Uranium) to achieve permanent bomb material source reduction.
- The *Remove* effort disposes of excess R/N materials from civilian sites thus resulting in eliminating bomb material availability threat.
- The *Protect* effort secures high priority R/N materials from theft and sabotage. The goal is to reduce the threat by improving the security of bomb making material remaining at the civilian sites and vulnerable buildings until a permanent threat reduction solution is implemented.

<u>Protecting civilian R/N materials</u>

It is important to note that this particular NNSA mission is different and in addition to the protection and safe handling of nuclear power plant Uranium-235 fuel wastes. R/N fuel waste of government or commercial utility nuclear power plants is well-regulated and tightly controlled. The uniqueness of the GTRI nonproliferation challenge is the focus on a large number of civilian organizations - such as hospitals, medical facilities, research labs, and industrial entities. Civilian organizations vary widely and use different types of R/N materials: americium-241, californium-252, cesium-137, cobalt-60, curium-244, iridium-192, plutonium-238, plutonium-239, radium-226, and strontium-90. There are thousands of such US civilian organizations. The number of civilian R/N material is high, and the sizes and form factor vary widely. Many of these nuclear sources have been abandoned as they are no longer in need. This makes them highly vulnerable to the threat of theft and sabotage. Such sites with dangerous material number in thousands globally.

There have been coordinated efforts addressing clearly regulated nuclear wastes such as ARGUS [12] by Argonne National Lab, intended for secure transport and monitoring of nuclear power plant spent fuels [13, 14], and MSTS [15] () by Pacific Northwest National Lab for mobile radioactive sources tracking and NNSA ORS (Office of Radiological Security). These solutions address applications such as nuclear power plant spent fuel rod transfer, with special form factors such as the container for the R/N fuel, and operation infrastructure requirements such as ARGUS' need to work with DOE infrastructure for cargo data collection, database, and web applications. These solutions were not designed to address GTRI's wide varieties of civilian R/N material types.

<u>Enabling protection of diverse civilian R/N material and operation scenarios</u>
SP, with its flexible application approach, can be applied to enhance existing R/N protection solutions targeting wide array of civilian R/N material targets. Diverse application scenarios could include:

- Logistics for national medical R/N material transport and storage
- Compliance monitoring for nation/state border crossing for export control and legal requirements
- Distributed R/N material integrity/safety monitoring and situation awareness against leakage, theft, and other anomalies
- Customized sensor technology and form factor for diverse civilian R/N material bearing devices shape and sizes.

Additionally, through 3D printing, smart and secure sensors could potentially be permanently embedded into the housings or the shells of the R/N material bearing devices such as the Iridium-192 bearing medical radiography device. Figure-8 shows Am241Be and Cs137 R/N material bearing well logging devices for underground oil exploration drilling operations. SP with 3D printed sensors/actuators into the shells of such devices could offer an integrated and permanent solution.

Figure-8 Potential SP 3D-printing integrated with well logging devices shields [15]

Cybersecurity in SP R/N Material Transport and Management

Cyber threats in edge computing

SP R/N material transport and management involves sensors and actuators. As a part of the advent of pervasive computing, these sensors and actuators bring exciting new opportunities. However, they also present cybersecurity concerns that come with modern edge computing. Such security threats may lead to compromises in system security architecture that could contribute to R/N material transport and management failures.

From the local perspective, SP sensors/actuators' hardware/firmware integrity and security need to be maintained to guarantee accurate monitoring and responses. From the global perspective, communication and information shared between SP sensors, readers, routers, and servers also need to be protected against cyber-attacks such as communication key cracking, session hijacking, man-in-the-middle attack, to ensure proper R/N material monitoring. If the communication is compromised, data can be falsified, removed, or blocked. Many protections are provided based on mathematically strong communication key technology. Fundamental communication key compromises could lead to a wide array of local and global failures.

Symmetric key communication and challenges

At the edge computing level, tiny sensors and devices lack computation power and memory or communication resources due to their size/battery limitation. This leads to limited computation power and communication bandwidth constraints. So, instead of using relatively secure but expensive (in computation and communication) asymmetric key based solutions such as PKI (Public Key Infrastructure), they commonly adopt symmetric keys for the communication among themselves and to the outside world. While secure by itself, state-of-the-art symmetric key solutions present realistic and unavoidable challenges when applied to the real-life scenarios such as R/N material transport and management. This is because symmetric keys, once they were given to the devices, cannot be made "forgotten" or "unlearned." As such, when a device is to be removed from a secure group, it will still retain the group communication secret key. In frequent re-grouping environments such as the R/N material logistics, large number of diverse R/N SP components, or groups of components, may be coming in-and-out to and from the shipment, stockpile, or cache. Expensive and frequent re-groupings will be required to maintain communication integrity. Frequent re-groupings require costly re-authentication, key-regeneration and re-distribution to maintain cyber security. Consequently, there is a need for a secure and efficient way to manage the life cycle of symmetric keys in this environment. This applies to the SP sensors/actuators, as well as to any other types of (e.g., radioactivity sensing) RFID tags, in order to guarantee R/N transport and management integrity.

7. FY23/24 PLANNING

The goal of the FY23/24 effort is to SP technology for NNSA tracking highly critical containers (such as: R/N shipments and storage) and prototype a smart tracker which works with T-STAR and can be integrated into new or existing R/N container solutions. This is an important effort to ensure safety, compliance, and operation quality of NNSA R/N material shipments.

Motivation

Smart Packaging's goal is to equip each package in transport with an edge computing device and set of sensors to provide the ability for real time network communication between each package's sensor suite and the cloud (e.g., via a telematics unit), enabling tracking and security, and safety monitoring. SP goes beyond just smart tagging of shipping or other formats of containers, and can involve modular, 3D-printed cargo containers with the desired edge devices and sensors "built-in". Furthermore, SP can provide a total packaging solution that is intelligent and active. On the one hand it monitors changes in a product or its environment (intelligent) and on the other hand it acts upon these changes (active) [1]. DOE's specific requirements will be different from other industries. It is our plan to examine these needs, identify and prototype the appropriate SP technology based on the need of the DOE scenarios.

Background

DOE customers have expressed interests in utilizing SP technology to improve multiple DOE critical operations, especially R/N material transportation and management. The potential DOE customers and use cases are:

- EM (Environmental Management) – Ensure transportation safety of R/N material, e.g., preventing leaking.
- ORS (Office of Radiological Security) – Secure delivery of R/N materials to hospitals (and other users/usages)
- NEO (Nuclear Energy Office) – Safe Small Modular Reactor (SMR) tracking and situation awareness

Goal

The desired outcome of this effort is to enable DOE organizations to fully utilize the state-of-art SP technology on R/N material transportation. R/N packages in transport will be attached to or contained within edge-computing SP devices. R/N with SP provides the ability for real time distributed network/cloud-based package tracking as well remote security monitoring. Furthermore, the enhanced SP capability to perform real-time monitoring on critical parameters such as temperature, vibration, radioactivity, and GPS location greatly enhances real-time situation awareness quality.

The impact of this effort is the overall improvement of DOE (R/N) transportation operation process bearing heightened security control and enhanced situation awareness.

FY23/24 proposed work

FY23 (350K)

- Phase 1: Architecture and testbed stand-up, est. completion FY23Q2
  - Architecture design, est. completion FY23Q1
  - Initial testbed, est. completion FY23Q2
- Phase 2: In-lab initial prototype, est. completion FY23Q4
  - In-Lab initial conceptual prototype with sensing and telematic functionality, deployed at ORNL's GEARS, est. completion FY23Q4
  - Design of Type B container appropriate for 3D printing, est. completion FY23Q4

FY24 (cost TBD)

- Phase 3: Final prototype, est. completion TBD.
  - Integration testing and validation at GEARS facility
  - Final prototype with 3D-printing
  - Report documenting design and validation results

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