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Impact of Novel Technologies on Nuclear Security and Emergency Preparedness

ERNCIP Thematic Group Radiological & Nuclear Threats to Critical Infrastructure

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Abstract

Novel technologies can benefit nuclear security and emergency preparedness in multiple ways. Generally, systems based on novel technologies are more flexible and can thus be quickly adapted to changes in the operational environment. In addition, these systems are more autonomous and are dependent on the expertise of the frontline officer.

The key emerging technologies for nuclear security and emergency preparedness include novel detection instruments, robotics, list-mode data acquisition and remote expert support. Novel technologies can reduce the size and cost of detection instruments while providing new features, such as automated source localization. Robots can automatically screen large areas and operate in environments with extremely high dose rates or the presence of other threats such as explosives. List-mode data acquisition is a compulsory requirement for many novel detection instruments and, thus a standardized list-mode data format is needed for sharing measurement data between different entities.

It is important to note that many novel technologies are not just direct, improved replacements for existing systems. Instead, to utilize the full potential of novel technologies, the concept of operation should also be modified. For example, instead of relying on fixed portal monitor installations where people and cargo must pass the detector one by one, novel technologies enable efficient screening of people and cargo in an unconstrained environment.

Adaptation of novel technologies also has major challenges. One challenge is that most technologies rely heavily on reliable and secure data transfer capabilities. This makes the systems more vulnerable to both intentional and unintentional disruptions in the data transfer network. In addition, it would be unrealistic to expect that novel technologies could replace the existing systems at once. Therefore, new instruments must be operated alongside with legacy systems, which can be rather challenging if the old and new system require different concepts of operation.

1 Introduction

This document is an overview of novel technologies which are expected to influence radiation measurements for nuclear security and emergency management in the near future. Rather than going into technical details, it discusses the practical advantages and challenges of these technologies for end users. A supportive document on *Novel Detection Technologies for Nuclear Security* (Ihantola, 2018) provides a more detailed description of novel radiation detection technologies.

The key tasks to be fulfilled with radiation measurements are often similar across all nuclear security and emergency management applications. However, the practical implementation of the measurements can differ significantly depending on application-specific needs. The common tasks and different high-level concepts of operation are discussed in Section 2. The requirements and challenges specific to certain applications (border control, law enforcement, emergency preparedness, radiological crime scene management, nuclear forensics and accident management) are presented in Section 3.

In the following sections, the document concentrates on the advantages and challenges of four emerging technologies: novel radiation detection systems (Section 4), robotics as detection platforms (Section 5), digital list-mode data acquisition (Section 6) and remote expert support (Section 7).

2 Concept of operation

Detection systems and related information management are often designed for the control of state borders. Another approach is to focus on the Interior Layer of the state (Major Public Events, critical venues or traffic nodes, such as railway stations). To achieve nuclear security goals and objectives, a concept of operations (CONOPS) should be developed identifying clear roles and responsibilities of each authority having jurisdiction. A CONOPS should address with the requirements of different detection architectures and different detection systems:

1. Primary screening with large (plastic) counters followed by secondary screening
2. Detection with spectrometric monitors (portals, backpacks)
3. Detection with mobile instruments (hand-held, backpacks, vehicles, drones).

The first approach works well for states which can allocate personnel for secondary measurement, although the false alarm rate could be high. The second approach may be selected by states which aim at minimizing false and innocent alarms at an early stage of detection (in order to minimize human resources); the implementation requires real-time reachback services, including high-quality analysis capability and reliable communication links. The third approach is based on relocatable, wearable, handheld, vehicle-based or other type of mobile detection instruments which are deployed according to intelligence or information alerts. In all cases, well-organized and efficient expert support is required to launch a fast and balanced response when needed.

A CONOPS deals with the roles and responsibilities of different competent authorities. The technical, scientific and operational tasks include

1. Detection
2. Identification
3. Localization
4. Material characterization
5. Alarm adjudication

(a) Initial assessment (front line officers + reachback)

(b) Assessment process (reachback + command & control)

(c) Threat and risk assessment

6. Response or interdiction

One major task is to understand if the detected signal is of natural origin. This is normally done in step 5, "Alarm adjudication".

The CONOPS is situation-dependent. For example in border control, a constrained environment, such as a designated point of entry (controlled border crossing), requires different organizational structures and detection systems as an undesignated point of entry ("green border" or coast). A Major Public Event (MPE) needs specific security and response measures for nuclear security. The related CONOPS should be generic enough to allow the lead organization carry out detailed planning and resource allocation.

3 Functional requirements

In most concepts of operations discussed in Section 2, the user of the detection equipment is typically a frontline officer with limited understanding of radiation. The frontline officer also needs to perform multiple tasks at the same time and possibly also deal with other sources of danger, which may render the presence of radioactive materials secondary in their operating procedures (up to a certain level of radiation threshold). Recent experience suggests that security staff is also constantly changing, making personnel training extremely hard. These problems reveal the need for further development of the widely used instrumentation to reduce the needs of training and user interaction.

3.1 Border control

3.1.1 Customs (Designated point of entry)

Frontline officer tasks at customs include conducting primary and secondary inspections of vehicles, cargo, passenger cars and pedestrians. Primary inspections are usually done at choke points of traffic (e.g. border crossing points) by monitoring the flow with fixed instruments (RPM-s) and wearable devices borne by frontline officers (PRD-s), or at loading sites (e.g. harbors or ships) by screening the cargo with handheld and wearable devices (e.g. RID-s and backpacks). For primary inspections, the emphasis is on the most effective detection of illegally transported materials.

At checkpoints, the measurement conditions can be nearly ideal by choosing the most suitable location (e.g. low natural background), and by slowing down the traffic. Primary inspections are usually done by non-expert personnel, who would require user-friendly interfaces and easily interpretable measurements results, for example "stop or go" indication for portals, or "red or green" alarms for personal detectors. In case of alarm, the primary screening could be repeated with the same instrument to eliminate false alarms, or the vehicle or person in question could be immediately redirected to another location for secondary screening. As the locations of the inspections are predetermined, the measurement conditions are usually well known, the secondary equipment could be easily and quickly reached, and integration with other systems (e.g. X-ray imaging) is possible. During secondary inspection, the aim is to localize and identify the source of radiation. The needed capabilities to reach this aim can be integrated either in the portal monitors (e.g. radiation mapping of vehicles), or in handheld equipment (e.g. RID-s). The equipment should enable the users to decide whether the alarm was real or innocent, and if they need to detain the subject and call expert support.

At loading sites, primary and secondary screening is usually done by local, specialized teams, using a set of handheld or wearable devices capable of high sensitivity detection, localization and identification. The measuring environment can greatly vary depending on the current location and structure of the cargo containers, or the structure and building materials of the ship. Localization and wireless communication capabilities can be well utilized in this environment.

Larger cargo containers make the usage of significant amount of shielding material for gamma radiation possible. For this reason, neutron detection capabilities and integration with active interrogation systems are highly recommended.

3.1.2 Frontier guard (Undesignated point of entry)

Nuclear security tasks on the green borders, or undesignated points of entry is closely related to the supervision of the flow of people, vehicles and goods on the borderline, where designated inspection points are not available. The surveillance of these areas is the primary task of the frontier guard organizations, thus the task of primary detection of radioactive materials could be integrated in their procedures.

The areas monitored include the lands between official point of entries, coastal shoreline regions, maritime craft screening and general airspace monitoring. Due to the nature of these areas, the detection of hazardous materials cannot be managed by fixed monitoring systems, while the expanse of the areas to be monitored makes the task very resource intensive.

Drones provide a good solution for covering large areas within a relatively appropriate timeframe, but the significant distance and the relatively small detector sizes make the detection of smaller amounts of radioactive material very difficult. The combination of motion detection and optical recognition with the primary detection of these materials could provide an advanced efficiency even for AI based robotic systems. Vehicle or aircraft based systems provide a wider range of applicable detection systems, but the primary detection of inapposite objects or people would be still a major task to enhance efficiency.

The survey of maritime crafts favors the application of body worn devices that provide a proper detection efficiency for multiple radiation types (e.g. gamma-neutron backpacks), or ship-based mobile detection systems.

3.2 Law enforcement

3.2.1 Public area patrol

Law enforcement agencies should be able to initially detect radioactive materials out of regulatory control, in normal operation conditions. Normal operations include for example routine roadside checks by the police and patrols on busy streets. Primary detection is usually done by non-expert personnel and, because of the relatively rare occurrence, the detection of radiation is not a primary task of frontline officers. For this reason, detection equipment should be wearable and small, and should require minimal or no active usage from the wearer. Because of the extremely high number of frontline officers, low price is a priority in most cases. On the other hand, the high number of officers could make it possible to integrate the devices in an extensive area monitoring system, consisting of several smaller detectors with GPS mapping capabilities. The presence of radioactive material in public areas could either mean criminal activity, or legal transport or usage of isotopes (e.g. medical isotopes for diagnostics), but in both cases, discretion in alarm assessment is preferred. In case of an alarm, measurement could be repeated with the same instrument. If the possibility of criminal activity cannot be excluded, a special unit or expert support is called.

3.2.2 Major public events

Special units are specially trained teams who have experience and knowledge in the detection of radioactive materials. These teams usually can be utilized in events or places where the occurrence of radioactive material has a significant possibility (e.g. surveillance of major public events). In these cases, a large variety of devices can be used, for example high sensitivity relocatable or mobile portal monitors, backpacks and RID-s, all preferably in covert mode. The special unit usually has to move around the area, while the vehicles and pedestrians are moving on undefined routes, so the measuring environment can rapidly change. These circumstances require good stabilization and background reduction capabilities, location indication, and possibility to quickly distinguish innocent and real alarms. Special units usually have a local command center and are in close connection with other expert support teams such as bomb squad. For this reason, wireless communication and GPS mapping is preferred. In case of a radiological event, measurement data and event logs could be sent to expert support, and quick response actions require having standardized report formats, that can be easily processed by all the relevant organizations.

3.3 Emergency preparedness

The primary task of emergency preparedness organizations is to respond quickly to emergency situations, such as disasters, accidents, and terrorist attacks. Situational awareness has been identified as one of the most critical aspects of the coordination of emergency response (Karagiannis & Synolakis, 2017). Emergencies seldom include the presence of radioactive material (e.g. natural disasters, fires, road accidents), and response teams are usually not prepared to deal with situations including radiological hazards. If no preliminary information is available regarding the presence of radioactive materials, primary detection is usually done by non-expert personnel (e.g. paramedics, firefighters). When responding to an emergency, first responders are heavily occupied with multiple tasks (e.g. use of specialized equipment and protective clothing), which usually don't allow them to deploy radiation detection equipment. In some cases, information regarding the presence of radiation can be more distracting than helpful for the user. For this reason, the priority for the equipment is to give indication for the users if the hazard level of the radiation is dangerous for their health. An alarm should be given if the dose-rate level or the accumulated dose is too high, if the activity concentration of the air is significant, or in the presence of alpha contamination in the area. GPS mapping and alarm forwarding towards the central station can be an important feature, because in these cases, coordination is vital. As the number of employees in emergency preparedness can be extremely high, a reasonably low price for detection equipment is needed. Equipping emergency preparedness vehicles with radiation detectors could be a partial solution, especially if the detectors are integrated with a mapping system, continuously reporting to a central alarm or reachback center.

Special units are deployed to carry out the technical response if preliminary information about the presence of radioactive material is available. These teams can focus either on a wide range of threats (e.g. CBRN-E of HAZMAT teams) or solely on the radiological aspect (e.g. decontamination teams). Specialized units can use a variety of transportable or relocatable systems, RID-s, backpacks and contamination monitors in addition to radiation protection devices. In this case, users are usually heavily equipped with other devices or protective clothing; therefore relatively lightweight, hands-free devices are preferred. The changing environment requires devices to have good stabilization capabilities, GPS mapping and wireless communication, adaptability to rapidly changing radiation levels, and location indication.

3.4 Radiological crime scene management

Radiological Crime Scene Management (RCSM) is defined by the IAEA (2014) as a the process used to "ensure safe, secure, effective and efficient operations at a crime scene where nuclear or other radioactive material are known, or suspected, to be present". Special requirements for RCSM arise from the need to ensure the radiological safety of personnel, the presence of radioactivity on or in pieces of evidence and the presence of contamination patterns, which should also be treated as part of the evidence. Novel technologies can make it easier to ensure safe working conditions for personnel (e.g. by remote operated detectors with drones or with more sensitive detection methods). Working conditions for personnel can be improved (e.g. with advanced PPE which is less stressful to wear or with improved dosimetry and automated checks and limits for working hours in the scene). New detection technologies can also make additional information available (e.g. visualize a relatively low radiation field with more sensitive gamma cameras) or solve conflicts between forensics and radiation protection (e.g. by making contamination detection possible without swipe samples).

Generally any technological advancement that will reduce the need for personnel working in radiation fields or a radiologically contaminated environment, simplify the recognition of contamination patterns, or simplify the handling of radioactive pieces of evidence will improve RCSM.

3.5 Nuclear forensics

Nuclear forensics is an important part of national and international response plans for incidents involving nuclear or other radioactive material out of regulatory control (ITWG, 2019; IAEA, 2011). A nuclear forensic analysis is carried out as part of an overarching police investigation and supports the investigation by providing insight into the history and origin of nuclear and radioactive material and its possible links to suspected perpetrators (Mayer, 2013). This is achieved through the collection and preservation of radiological and nuclear evidence and through the analysis of this evidence using suitable methods, including non-destructive and destructive techniques, both at the scene and in the laboratory. Novel technologies that simplify the documentation of evidence (for example through automated sample logging combined with three-dimensional scanning) and improve the non-destructive, preferably remote, radiological and nuclear analysis will impact nuclear forensics and advance the field considerably.

It is of the utmost importance that the relevant chain of custody restrictions be observed, in order to ensure that the results of a nuclear forensic analysis can be admitted in court. Novel technologies that provide automated documentation and data collection to a standard that is acceptable to court procedures, whilst simultaneously being able to handle sensitive police data (classified as restricted or above) will improve the observance of the chain of custody. Some pieces of evidence may contain mixed hazards (CBRN and/or E). For this reason, novel technologies that can rule out the presence of explosives in a piece of evidence contaminated with radiological or nuclear material before it is transported to a laboratory can be a significant improvement. It is essential that nuclear forensic techniques and methods be suitable, effective and represent international best practice, in particular when an incident requires cooperation between states (for instance, in illegal cross-border trafficking of nuclear material out of regulatory control).

3.5.1 Nuclear forensics laboratory techniques

As stated above, it is essential that nuclear forensics techniques be suitable, effective and represent international best practice. The laboratory techniques for nuclear forensics are beyond the scope of this document. However, there are many areas in nuclear forensics laboratory work that could be improved by the use of novel technologies, including, among others, LA-ICP-MS, XRD, activity mapping, autoradiography, micro-analytical techniques, luminescence dosimetry and biological dosimetry.

In particular, novel technologies, including artificial intelligence (AI), could be used to support the interpretation of lab-based data collected during an investigation, for instance fitting of alpha and gamma spectra, and also to support statistical analysis, especially if two samples need to be compared or if a search for a match in a database (national nuclear forensics library) is required. AI could also be used to match the information gained from the investigation to open source information (e.g. press reports, published scientific articles). This in turn would support the information available to the nuclear forensics practitioners in the laboratory, although it cannot replace the knowledge and wisdom of nuclear forensics experts. Another novel idea would be to use blockchain technology to support the documentation of the chain of custody: individual institutions would not be able to change the records of the samples location without the permission of all the institutions involved. This would help to reduce the potential for manipulation from inside the competent authorities (insider threats) and would make the process more transparent.

This document does not discuss these topics further. The gap identified in the scope of this document presents opportunities for future work to improve laboratory techniques used in nuclear forensics through the use of novel technologies.

3.6 Accident management

The advantages of robotics in nuclear severe accident management and mitigation can be found in the limitations of human intervention capabilities in beyond design basis events induced by external natural hazards (either individually or in combination). These limitations have also plagued the strengths of current PSA (probabilistic safety analysis) and DSA (deterministic safety analysis) methodologies that have, post-Fukushima, accepted the difficulty in human reliability analysis concerning human activities in relation to severe accident management and mitigation (SAM+M) and the execution of such measures. This issue is especially more important when dealing with multi-reactor sites and sites combined with spent fuel pools or other significant radiation sources. This has resulted in IAEA documentation as well as NRC and EU-stress-test documentation (in general or nuclear governing bodies) accepting that currently the reliance on SAM and mitigation strategies as an effective defense against natural hazard triggered beyond design basis severe nuclear accidents is speculative at best. This is due to the limitations of human intervention capabilities in such circumstances. It can be said that the more comprehensive a probabilistic and deterministic safety analysis of a nuclear power plant, the more the weakness of human and organizational factors comes to light (in the form of feasibility of operator actions), thus the use of robotic applications becomes extremely significant in this regard.

3.7 Cross-cutting elements

3.7.1 Cyber security

Secure and reliable data communication is a vital requirement for the use of many novel technologies. Specifically, three factors must be taken into account in the design of the data communication architecture. First, uninterrupted data communication must be guaranteed regardless of unintentional or intentional (malicious act) disturbances in data communication. One approach to improve reliability is to have several redundant methods for data transmission. Second, unauthorized access to the data must be prevented. This can be achieved, for example, by using strong encryption algorithms. Third, the malicious injection of falsified data into the system must be detected. The identity of the sender and the integrity of the data content can be verified, for example, with digital signatures.

3.7.2 Training

Training and exercises are of vital importance for handling nuclear accidents and threats. The contents of the events can be tailored for different target groups such as incident commanders, reachback experts and first responders. Nuclear experts play a key role in the design, conduct and evaluation of training courses and exercises.

Implementing realistic nuclear security scenarios is difficult with real radioactive sources. For safety reasons, only small amounts of radioactivity can be used, particularly in urban areas. However, small sources are unsuitable for teaching safe and efficient search tactics in scenarios where measurements take place far away from the source.

A Table Top Exercise (TTX) may be designed for a nuclear accident or the detection of and response to an unauthorized or criminal act involving nuclear or other radioactive materials that are out of regulatory control. A TTX mimics law enforcement techniques and radiation detection capabilities for handling the event, including criminal investigations. Often this work is supported by a Reachback Center.

Recently a digital platform was introduced for TTX (Toivonen, 2018); software generates radiation measurements in real time reflecting actions of the trainees. Simulations, combined to realistic nuclear security scenarios, provide excellent means for training and exercises. Understanding the real-world challenges and requirements are the basis for choosing the detection instruments and establishing an efficient and secure information sharing mechanism between the authorities.

4 Benefits and challenges of emerging detection systems

4.1 Benefits

Emerging radiation detection technologies can improve many features already existing in current radiation detectors. For example, novel gamma-ray scintillator materials (see Section 2 in Ihantola (2018)) can provide significantly better energy resolution than older detectors. This improves the reliability of source identification and reduces the number of innocent alarms. Novel neutron detectors (see Section 3 in Ihantola (2018)) have high neutron detection efficiency and good discrimination of gamma-rays. Therefore, they can detect weak neutron signals even under high gamma-ray exposure. This is especially important for the detection of shielded neutron sources or neutron sources masked with legal transportation of gamma-ray sources.

Novel instruments can also contain completely new features. For example, the radiation sensor may automatically localize the source of radiation (see Section 7 in Ihantola (2018)). The instruments can also contain multiple non-radiological sensors such as 360-degree imaging cameras, GPS transceivers and rangefinders. Smart detector instruments can combine the data from multiple radiological and non-radiological sensors and, for example, present a 3D model augmented with radiological information or track the movement of a source. The detector can also guide the user to optimize measurements. If expert support is needed, the systems can automatically transfer the data to a reachback center for further analysis. Comprehensive data enables the radiation experts at the reachback center to obtain a better understanding of the situation, which reduces the need to travel on site to conduct secondary measurements.

Novel technologies also enable building smaller and cheaper radiation detectors. This results from the development in three different fields. First, sensors sensitive to both neutrons and gamma rays (see Section 4 in Ihantola (2018)) remove the need for two detector elements. Second, compact semiconductor photosensors (see Section 5 in Ihantola (2018)) can replace photomultiplier tubes, which are often the bulkiest and most fragile components of scintillator gamma-ray spectrometers. Third, recent progress in electronics has made possible the development of data acquisition systems that are not only extremely compact but also have extensive features and low power consumption (see Section 6 in Ihantola (2018)). Due to the reduced cost and size, the number of detectors used by frontline officers can be drastically increased. This will increase both the sensitivity and resilience of such instruments, due to the reduced impact of a single equipment failure to the total detection capability.

Overall, emerging technologies can reduce the operational costs of radiation measurements while improving the throughput of people and cargo. As a general trend, the novel detectors provide more comprehensive and better-quality data, can operate more autonomously, and are less dependent on the expertise of the user than the instruments currently in use. Since a larger part of the analysis is done automatically or remotely, radiation experts are seldom needed in the field. Flexible detector systems also improve the sustainability, because the same devices can be deployed in multiple ways depending on the risk assessment or other changes in operational environment.

Novel instruments can help in all six tasks (see Section 2, Concept of operations) required for the detection of radioactive materials out of regulatory control:

1. Detection
    - Detectors with higher sensitivity enable the detection of shielded sources or sources at a greater distance
    - Better-quality data enables reduction of false alarms
    - The larger number of relocatable detectors enable the optimal deployment and redundancy on equipment failures
2. Identification

- Spectrometric detectors with smart analysis algorithms can improve the reliability of identification and reduce the need for secondary measurements.

3. Localization
   - The source localization can be done either fully automatically or in a semiautomatic way where the system guides the frontline officer.
   - Source localization methods can use the data from multiple detectors connected to the same network.
4. Material characterization
   - With advanced analysis algorithms, the shielding around the source can be estimated based on the measured gamma-ray spectrum .
   - By combining the information on the possible shielding with the location of the source (step 3) and isotope identification (step 4), an estimate for the source activity can be automatically calculated.
5. Alarm adjudication
   - With automated data transfer to reachback center, a radiation expert can perform the alarm adjudication without a need to travel on site.
   - Comprehensive data improves situation awareness at the reachback center, improving the reliability of the alarm adjudication done remotely.
6. Response or interdiction
   - Thanks to the enhancements in steps 1-5, the response system becomes more agile.
   - A highly automated analysis pipeline also reduces the possibility for human errors.

4.2 Challenges

A major challenge for the use of emerging technologies is the transition from current systems to the new ones. Due to the high cost of the equipment, it is unlikely that all radiation detectors would be updated at once. Thus, the old and new detector systems need to be able to be used in parallel. Resistance to change can also significantly slow down the use of novel technologies, especially if the change makes local radiation experts redundant.

It is also worth to point out that even the latest radiation detectors will become legacy systems in the future. Generally, the development of radiation sensors is much slower than the development of data transmission methods, data formats and analysis algorithms. For example, fully working radiation sensors may be discarded because the proprietary output data format is no longer supported. The lifetime of radiation detectors can be significantly expanded equipment is designed with sustainability in mind. Simple approaches for improving sustainability include the use of open data formats and communication protocols, and a possibility to update the built-in analysis methods.

The key to successful adaptation of emerging technologies is not to solely concentrate on the technology but also to rethink the entire concept of operation. If the concept of operation is not updated to match the opportunities and requirements of the new technical systems, the practical benefits can be minimal. For example, reachback centers with high level of expertise are required for the validation of different types of information provided by novel detectors.

Novel detection systems also set new requirements for the infrastructure. If secondary analysis of data is done remotely, reliable data transfer between the detector units and reachback center must be guaranteed. The data transfer may be obstructed both unintentionally (equipment failures, poor wireless connection) or intentionally (cyber-attacks). Complex detector systems may also need more maintenance in the long run than the relatively simple detectors currently in use.

5 Benefits and challenges of robotics

Critical infrastructures like bridges, railways or nuclear power plants require regular inspections and maintenance, but also safe demolition and fast response in case of disasters. This kind of operations usually involves high-risk tasks for workers, but also for the nearby population in general. European Union directive (European Commission, 2014) stipulates that the effective dose limit for occupational exposure is 20 mSv in any single year. Clearly there is a need to replace the human worker on daily base maintenance work and especially in the case of emergency situations and nuclear decommissioning.

Autonomous or remotely operated robotic solutions could be of a great help to this kind of operations, making them a lot safer and easier to process. Examples for such scenarios include decommissioning of nuclear power plants, clean up after landslides, demining or cleaning munitions dumps and crime scene investigations after terrorist attacks involving hazardous materials.

There is significant potential for the use of unmanned systems in scenarios involving radiological and nuclear threats. One of the main inherent advantages of robots in these scenarios is the protection of responders. Unmanned systems can operate in environments that under normal conditions are inaccessible to humans. Since the operating time of a robot is generally only limited by the battery charge, it also facilitates 24/7 operations. Other benefits of unmanned systems include their capabilities to:

- operate in areas with high radiation, as well as explosive hazards, collapsed structures, IEDs, heat;
- take and manipulate samples;
- take long-time measurements and survey contaminated areas;
- monitor the movements of a (potential) threat; and
- provide real-time data from multiple on-board sensor source.

Besides these response scenarios, unmanned systems also allow dirty, dull and dangerous repetitive work in pre-disaster or security-related operations. One application is the exploration and mapping of large areas. A typical example is a container port that has to be monitored for illicitly trafficking potentially dangerous radioactive material. Quite similar are scenarios which involve extensive patrolling, e.g. prior and during a major public event. These activities would include the detection and identification of illicit transport or possession of radioactive sources or nuclear material.

In the case of a suspicious object the robot could improve situational awareness by determining the location and characteristics of the radioactive object. If the location of the source or contaminated area is only roughly known, the unmanned system could be tasked with creating isocurves for dose rate (radiation heat map).

Once the location is identified, the robot can be used to take samples or manipulate the potential threat. The manipulation might include sorting (e.g. of scrap metal or container content) and moving the threat object to a safe location (e.g. by placing it in a safe container).

Because of its rich endowment with multiple sensors, the robot is able to contribute enormously to situational awareness. Not only will it deliver real time video, but, equipped with 3D laser scanners, it may also provide virtual reality output. This will allow the operator to be on-site. The virtual reality environment can be attributed by real time RN measurements and accumulated measurements of a longer period of time.

There are challenges to utilizing robots in nuclear safety. For example, major parts of reactors that are currently operational were commissioned before 1990. That time mobile robotic systems were still on their infancy and hardly used. Nuclear power plant infrastructures are not designed to support mobile robots. Also, nearly all are unique in design, which means that the robots so far successfully operational have been designed and tailored to a specific environment. Also, existing robot technologies have only proven to be useful to assess a situation, but they are often too immature or fragile for the use in real decommissioning, clean-up, or deconstruction.

Fortunately, nuclear power plant accidents are very rare. Major accidents, such as the Three Mile Island and Chernobyl disasters happened before the mobile robots were really ready. The last big accident in Fukushima confirmed drastically how important it is to confirm the site condition as soon as possible after the nuclear accident to provide reference information for emergency disposal. Clearly collaborative robotics approach could and should have been used. There would have benefits of team effort of UAV, UGV and even USV to map the situation quickly and plan the recovery operations more precisely.

In conclusion, robotics would be a major asset and contribution to all these applications as well as to those named in chapter 3. To fertilize the application of robotics in these fields, the standardization process with regards to interfacing and interoperability needs a significant boost.

Currently four communication sites can be identified:

1. between sensor and robot
2. between robot and operator control unit (OCU)
3. between the robotic system (robot + OCU) and the levels of the strategic-tactical–operational command structure
4. additional communication within Civil-Military Co-operation (CIMIC)

To enable the experts and decision makers to build up a real-time situation awareness the data acquired by the robot needs to be communicated seamlessly and loss-less. This complex communication path needs to be systematically explored.

6 Benefits and challenges of list-mode data acquisition

List-mode data acquisition is the technique of recording data obtained from the individual pulses observed directly at the detector output. The technique has already been in use for a few decades, but its real advantages emerge when applied to novel detector systems using high-performance digital electronics, especially in applications where time-correlated data from one or several detectors is to be combined (Ihantola, 2018).

For example, in nuclear security (see Section 2, *Concept of operations*), the availability of timestamped list-mode enables the automatic rejection of nuisance alarms caused by coincident neutrons generated by cosmic radiation and therefore improves the sensitivity of the detector system to nuclear material. More recently developed systems, such as Compton imagers and advanced muon tomography systems, rely on timestamped data to operate.

Because list-mode data acquisition with high-performance digital electronics observes the signal directly at the detector output and because all settings and parameters affecting the data acquisition process can be remotely set by software, the technique enables remote diagnosis of underperforming or malfunctioning detectors. Equipment manufacturers have the specialized knowledge in digital systems and can connect to the systems for remote diagnostics. For a number of cases, the technical expert no longer needs to go onsite to adjust the system (see Section 3, *Functional requirements*).

To realize improved or centralized alarm adjudication, or to fully profit from integration between systems or to combine data from mobile systems used in any of the scenarios from Section 3, more comprehensive and detailed data needs to be shared. Similarly, as discussed in Section 4, to fully exploit novel detection instruments, the comprehensive data produced by them shall reach the reachback center untampered over a reliable connection.

It is thus clear that standards play an important role in enabling interoperability between these systems' hardware and software. Data format standards are an essential first step in improving interoperability. While the well-established data format standard IEC 62755 (identical to ANSI N42.42) provides a solution at a higher level, it is not suitable for sending low-level list-mode data. IEC 63047 is a binary data format standard for list-mode data and complements IEC 62755. The ERNCIP RN TG had a key role in developing the list-mode data format standard IEC 63047, which was published in October 2018. The standard provides the necessary features to represent data extracted from pulses observed at the detector output. In addition to this pure list-mode data, the standard IEC 63047 can be used to represent other types of data such as geolocation information and spectra. The latter have been included deliberately to support the transition phase from conventional electronics to digital instrumentation (Section 4.2).

One challenge for integrated systems that need to share more comprehensive and detailed data is the availability of reliable and secure network connections with sufficient bandwidth. Inevitably, requirements for data storage will increase.

When timestamped list-mode data from spatially separated systems needs to be combined, the systems need to be accurately synchronized. It is challenging yet feasible to realize such synchronization for unwired (e.g. mobile) systems. For example, time synchronization with an accuracy below 1 ns can be realized via GPS receivers that have multiple satellites in view. While this is generally sufficient for most applications, some applications using fast detector materials may require timestamp accuracy a few orders of magnitude lower.

Low-level data format standards such as IEC 63047 improve the interoperability between hardware and software. While this is expected to be a bliss for system integrators and developers of software systems for data analysis, the success of the standard will depend on the willingness of manufacturers who offer complete systems to implement the standard as an alternative to the proprietary data format that they use between the hardware and software component.

7 Benefits and challenges of remote expert support

The use of detection instruments in nuclear security has a fundamental and disparate problem: reliable and timely detection and characterization of threat materials without disturbing innocent people or legal transport of goods. Ever more advanced novel technologies will be available for detection efforts. Efficient handling of the information produced by these systems may be difficult.

Expert support (reachback) is a solution to technical and scientific information management. Expert support can be provided locally by the presence of nuclear experts or remotely via information sharing between field operators and off-site nuclear experts.

Remote analysis capabilities may change the way detection instruments operate in the future. Not all functionalities need to be embedded in the instrument itself; the most demanding analyses can be performed at a remote server under the control of dedicated subject matter experts. The quality and speed of measurements, combined with timely and correct analyses, are vital operative requirements.

7.1 Expert support – minimum requirements and capabilities

Expert support is a cross-cutting element in nuclear security. It can be arranged in different ways for different national security systems and can address technical, scientific or operational issues. Radiological and nuclear expertise is needed for various tasks, such as operation of detection systems, data analysis, alarm adjudication, threat and risk assessment, safety of personnel, nuclear forensics and advice to law enforcement and other authorities. The national nuclear security framework defines how these tasks are allocated to authorities and other stakeholders.

To establish an expert support capability, material and human resources need to be addressed in the field and at the reachback center. The functionalities must be designed jointly with the authorities having jurisdiction. Capability testing, training and exercises provide the basis for efficient operational detection and response.

A national expert support system is of vital importance in the fight against criminal or unauthorized use of nuclear or other radioactive materials. The expert support system should have a legal status in the national nuclear security framework, including clear roles and responsibilities. A well-organized expert support system has a capability to provide radiological and nuclear advice to responsible authorities 24/7.

A reachback center provides reliable and remote radiological and nuclear support to units in the field. The operational aim is to distinguish between false, innocent or true alarms. Experts are also needed for managing possible radiological safety issues and to assess whether the alarm has security implications.

Radiological and nuclear threats have a low likelihood of occurrence but potentially extremely severe consequences. A high-impact, low-probability event calls for cooperation at the national and international level. It is not justified that all authorities in all EU Member States should have all possible technical and scientific capabilities at their disposal. For cooperation, a bilateral agreement on expert support with another EU Member State, or with an organization, could be a fundamental component of a national expert support system. Before such support is possible, national political and administrative measures have to be in place: receiving help is only possible if a mechanism for that exists (Tengblad, 2019).

7.2 Threat material characterization

Activity estimation of radioactive sources is a well-established technique in laboratory conditions. However, field measurements are much more complex because of the unknown measurement geometry, including the shielding between the source and the detector. The source could be heavily shielded, the signal being small, but the actual activity still very large.

Two methods have been identified for estimating the activity of the source based on the gamma-ray spectrum recorded in field (Toivonen, 2017). In the first method, the relative peak areas of different gamma lines emitted by the same radioisotope are used to determine the attenuation caused by the shielding. A disadvantage of this so called peak ratio method is that it does not work for single line emitters, such as Cs-137. The second method utilizes the gamma-ray photons that scatter from the shield, increasing the gamma-ray spectrum baseline on the low energy side of the full energy peaks. In this step ratio method, the attenuation is estimated based on the ratio of the scattered and un-scattered photons. The biggest challenge of both methods is the uncertainty analysis and production of the required calibration data.

One practical approach to utilize the full gamma-ray energy spectrum in the data analysis is to compare the unknown spectrum with well-known and documented reference data. The comparisons are fast to do and produce convincing outcomes, i.e., it is evident whether there is a good match between the unknown and reference spectra. Building a comprehensive reference data library is the key to success.

The activity calculation, containing shield analysis, is not a task of the frontline officers. Such analyses belong to nuclear experts, and can be best performed in a dedicated reachback center.

7.3 Network of detection systems – need for reachback

A single isolated instrument is only useful at the site of deployment, and it may or may not resolve adequately the collected signal. Sometimes the situation may be very complex; the collected signals may be weak and by no means easy to interpret. If the instrument would be connected to a larger data processing system, it may be possible that the entire system would be sensitive enough to provide adequate information for alarm adjudication.

An example of network processing capabilities is the source localization based on sensors which give the angle towards the source. The precise location of the source can only be calculated from two or more measurements performed at different places (triangulation). If the instruments report to a joint database, then the position of the source can be calculated in real time.

A proper operations center is a key cross-cutting element of a Nuclear Security Detection Architecture. It is supported by experts on radiological and nuclear detection capabilities, including alarm adjudication. Its role is to facilitate situational awareness and response coordination. To fully utilize the recent technical and scientific development in nuclear security, an advanced reachback center should be established. Data communication, processing and analysis must be well-organized for a timely and balanced response.

8 Discussion

Radiological or nuclear terrorism is a low-probability event. This may be the reason why the level of preparedness of states to handle nuclear threats varies widely. The readiness includes an up-to-date legal framework, implementation of preventive measures, building of sustainable detection architectures and planning for the response.

Novel detection technologies provide the means to improve the present readiness of the authorities to detect the threat early and to respond effectively. Detection sensitivity is improved by new detector materials and data acquisition systems; source localizers help to find the source; robots can be used 24/7 in dangerous situations and a network of detection systems is much more efficient than the individual isolated sensors.

New technologies as such in the present detection architectures may not provide all benefits. The instruments form the low-level detection system providing data and automatically processed information about the radiological situation. These unverified findings must go through an alarm adjudication process, which leads to "a verdict", to clear instructions what to do next.

If the detection architecture contains several sensors, maybe hundreds, the data management is in the key role. It not possible to have a nuclear expert onsite 24/7 to analyze the continuous flow of data. A better solution is to have a centralized data processing system controlling the overall network and radiation experts in readiness to support the law enforcement for a well-balanced and timely response. Full power of the novel technologies is achieved when CONOPS is reconsidered and the expert support plays a crucial role as a cross-cutting element in the detection architecture.

References

European Commission, *Council Directive 2013/59/Euratom of 5 December 2013 laying down basic safety standards for protection against the dangers arising from exposure to ionising radiation, and repealing Directives 89/618/Euratom, 90/641/Euratom, 96/29/Euratom, 97/43/Euratom and 2003/122/Euratom*, Off. J. Eur. Commun. 13, 2014.

IAEA, *Radiological Crime Scene Management*, IAEA Nuclear Security Series No. 22-G, Vienna, 2014, isbn:978–92–0–108714–0.

IAEA, *Nuclear Security Recommendations on Nuclear and Other Radioactive Material out of Regulatory Control*, IAEA Nuclear Security Series No. 15, Vienna, 2011, isbn:978-92-0-112210-0.

IEC*, Nuclear instrumentation - Data format for list mode digital data acquisition used in radiation detection and measurement*, IEC 63047, 2018.

IEC*, Radiation protection instrumentation – Data format for radiation instruments used in the detection of illicit trafficking of radioactive materials*, IEC 62755, 2012.

Ihantola, S., Tengblad, O., Toivonen, H., Peräjärvi, K., Csome, C., Borg, J., Paepen, J., Tagziria, H., Gattinesi, P., *Novel Detection Technologies for Nuclear Security*, EUR 29270, Publications Office of the European Union, Luxembourg, 2018, doi:10.2760/703301.

ITWG, *Web page of the Nuclear Forensics International Technical Working Group*, viewed March 2019, http://www.nf-itwg.org/

Karagiannis, G.M. and Synolakis, C.E., 'Twenty challenges in incident planning', *Journal of Homeland Security and Emergency Management*, Vol. 14, Issue 2, doi: 10.1515/jhsem-2016-0061, 2017.

Mayer, K., 'Expand nuclear forensics', *Nature News*, Vol. 503, No 7477, 2013, pp 461-462.

Tengblad, O., Tagziria, H., Eisheh, J.-T., Köger, E., Schoeh, H., Peräjärvi, K., Toivonen, H., *National and Cross-border Expert Support for Nuclear Security,* Publications Office of the European Union, Luxembourg (DRAFT), 2019, https://erncip-project.jrc.ec.europa.eu/system/files/Cross-Border-temporary-draft04022019.pdf.

Toivonen, H., Ihantola, S., *Scenario-based learning to manage nuclear threats in virtual electronic environment*, International Conference on the security of radioactive material: the way forward for prevention and detection, 3-7 December 2018, Vienna, IAEA.

Toivonen, H., Granström, M., Ågren, G., Jónsson, G., Møller, B., Roos, P., Ramebäck, H., *Activity estimation of shielded or hidden radionuclides in emergency conditions, NKS-399,* Nordic Nuclear Safety Research, 2017, isbn:978-87-7893-487-1.

List of abbreviations and definitions

AI	Artificial intelligence
CBRNE	Chemical, biological, radiological, nuclear and explosive materials
CONOPS	Concept of operation
DSA	Deterministic safety analysis
GPS	Global positioning system
IAEA	International Atomic Energy Agency
IED	Improvised explosive device
MPE	Major public event
PPE	Personal protective equipment
PSA	Probabilistic safety analysis
RCSM	Radiological crime scene management
RID	Radiation identification device
PRD	Personal radiation detector
RFID	Radio frequency identification
RPM	Radiation portal monitor
SAM+M	Severe accident management and mitigation
TTX	Table top exercise
UAV	Unmanned aerial vehicle
UGV	Unmanned ground vehicle
USV	Unmanned surface vehicle

Annex: List of publications of ERNCIP RN Thematic Group

List-mode data acquisition

Kari Peräjärvi, John Keightley, Jan Paepen, Olof Tengblad, Harri Toivonen doi:10.2788/88299 Luxembourg: Publications Office of the European Union, 2014, List-mode data acquisition based on digital electronics - State-of-the-art report

Jan Paepen, Magnus Gårdestig, Per Reppenhagen Grim, John Keightley, Jonas Nilsson, Kari Peräjärvi, Olof Tengblad, Harri Toivonen, doi:10.2788/66637, Luxembourg: Publications Office of the European Union, 2014, Critical parameters and performance tests for the evaluation of digital data acquisition hardware

Jan Paepen, John Keightley, Kari Peräjärvi, Olof Tengblad, Per Grim, Juha Röning, doi: 10.2787/041418, © European Atomic Energy Community, 2015, Standardisation of the data format for list-mode digital data acquisition: Survey results

Reachback

Harri Toivonen, Per Reppenhagen Grim, Olof Tengblad, John Keightley, Jan Paepen, Kamel Abbas, Frank Schneider, Jonas Nilsson, Kari Peräjärvi, doi:10.2788/20613, Luxembourg: Publications Office of the European Union, 2014, Remote Expert Support of Field Teams - Reachback Services for Nuclear Security

Harri Toivonen, Hubert Schoech, Per Reppenhagen Grim, Leticia Pibida, Mark James, Weihua Zhang, Kari Peräjärvi, doi:10.2788/718077, © European Union, 2015, National reachback systems for nuclear security

Harri Toivonen, Per Reppenhagen Grim, Hubert Schoech, John Keightley, Olof Tengblad, Frank Schneider, Carl-Johan Forsberg, Peter Gattinesi, Kari Peräjärvi, doi:10.2788/763983, © European Union, 2015, Information sharing in a nuclear security event

Olof Tengblad, Kari Peräjärvi, Harri Toivonen, Peter Gattinesi, doi: 10.2760/036282, Luxembourg: Publications Office of the European Union, 2017, After-action Analysis of the Magic Maggiore Workshop on Expert Support and Reachback

Olof Tengblad, Hamid Tagziria, Jens-Tarek Eisheh, Emily Köger, Hubert Schoeh, Kari Peräjärvi, Harri Toivonen, National and Cross-border Expert Support for Nuclear Security, doi: DRAFT. Luxembourg: Publications Office of the European Union, 2019, https://erncip-project.jrc.ec.europa.eu/system/files/Cross-Border-temporary-draft04022019.pdf

Robotics

Frank E. Schneider, Bastian Gaspers, Kari Peräjärvi, Magnus Gårdestig, doi:10.2788/60148, Luxembourg: Publications Office of the European Union, 2014, Possible scenarios for radiation measurements and sampling using unmanned systems

Frank E. Schneider, Bastian Gaspers, Kari Peräjärvi, Magnus Gårdestig, doi:10.2788/106167, Luxembourg: Publications Office of the European Union, 2015, Current state of the art of unmanned systems with potential to be used for radiation measurements and sampling

Frank E. Schneider, Bastian Gaspers, doi:10.2788/112402, EUR 27766 EN, Survey on the use of robots/unmanned systems in scenarios involving radiological or nuclear threats

Frank E. Schneider, Bastian Gaspers, John Keightley, Juha Röning, Jan Paepen, March 2017, The unmanned systems trial for radiological and nuclear measuring and mapping

Novel Technologies

Sakari Ihantola, Olof Tengblad, Harri Toivonen, Kari Peräjärvi, Csilla Csome, Johan Borg, Jan Paepen, Hamid Tagziria, Peter Gattinesi, doi:10.2760/703301, May 2018, Novel Detection Technologies for Nuclear Security

Other publications

Harri Toivonen, doi:10.2760/89876, Luxembourg: Publications Office of the European Union, 2016, Summary of the Activities of the RN Thematic Group in 2016

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