Integration of independent NDA techniques within a SLAM-based robotic system for improving safeguards standard routines: a review of the current status and possible future developments

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Abstract:

Agencies devoted to safeguard and non-proliferation make large use of techniques based upon non-destructive assays (NDA) systems for ensuring the correctness of operator declarations about a facility inventory or for gathering data during inspections. The data ensemble to analyse consists of many aspects, but it is mainly focused on radiological data. De facto, systems used for NDA radiological characterization are optimized for precise goals in order to maximize their efficiency and ease of use, at the expense of versatility and more complete (although complex) results. Nevertheless, this approach may encounter several limitations due to the intrinsic properties of the techniques involved. For example, proper background estimation and subtraction in a gamma spectrometry are not always possible, either due to photons mean free path in matter or to the possible inability to suppress external contributions by placing the detector close to the item in object.

A Concept of a modular, multi-sensor system is presented, where the results of radiological and non-radiological assays are automatically integrated in a 3-dimensional model created by means of novel results in robotics and optical sensors. This review paper reports and discuss the state-of-art in the implementation of systems similar to the Concept presented, as the idea behind the Concept has already been tested in recent years with promising results; nevertheless, technology develops fast in the field and new future implementations, improvements and applications in safeguards and non-proliferation are worth to be envisaged, presented and discussed. For example, some of the Concept sensors can also be used as a stand-alone detector, with a natural gaining in the Concept versatility: a high-resolution gamma spectrometer can be used to measure Plutonium isotopic composition or Uranium enrichment. Moreover, results obtainable through the Concept can be used to create a digital twin of a generic component, system, or facility, complete with several radiological and non-radiological data, resulting in a dramatic step forward in the implementation of the Building Information Modelling (BIM) standards.

Keywords: safeguards, non-proliferation, SLAM, gamma imaging, BIM.

1. Introduction

Within the scope of safeguards and non-proliferation of Special Nuclear Materials (SNM), several tasks are accomplished by legally authorized agencies (e.g., the International Atomic Energy Agency, IAEA), including Design Information Verification (DIV), consistency checks on nuclear material accountancy, independent on-site inspections and unattended containment and surveillance (C/S).

Inspection of complex equipment and facilities processing or storing nuclear materials can be a very cumbersome process. For example, a change in the original facility design can suggest that its original purpose was altered, which can suggest malicious proliferating intentions. Visual inspection is not always a reliable way to identify changes in the facility design, but in last years it has been supported by 3-dimensional reconstruction methods like the 3D DIV, a way to create a time-trackable 3-dimensional map of a generic site by means of devices like Laser Scanners or LIDARs (LIght Detection And Ranging) [1]. Moreover, similar optical techniques are used to ascertain seals' integrity.

Periodical inspections, on the other side, usually rely on independent radiological characterization measurements, by means of Non-Destructive Assay (NDA) or Destructive Assay (DA) depending upon the goal of the campaign. NDA characterization is performed in-situ using systems both available off-the-shelf (COT) or specifically tailored to reach precise goals, like quantifying Uranium enrichment, establishing Plutonium isotopic composition or estimating the fuel burn-up through fissile products. Depending upon the measurements' scope, the systems used are equipped with detectors, electronics and software with characteristics developed to optimize the assay. In this sense, efficiency and ease of use are often preferred respect to versatility (which often hides complexity). Nevertheless, standard safeguards routine using non-destructive assays may face several limitations, like the impossibility/inability to get close

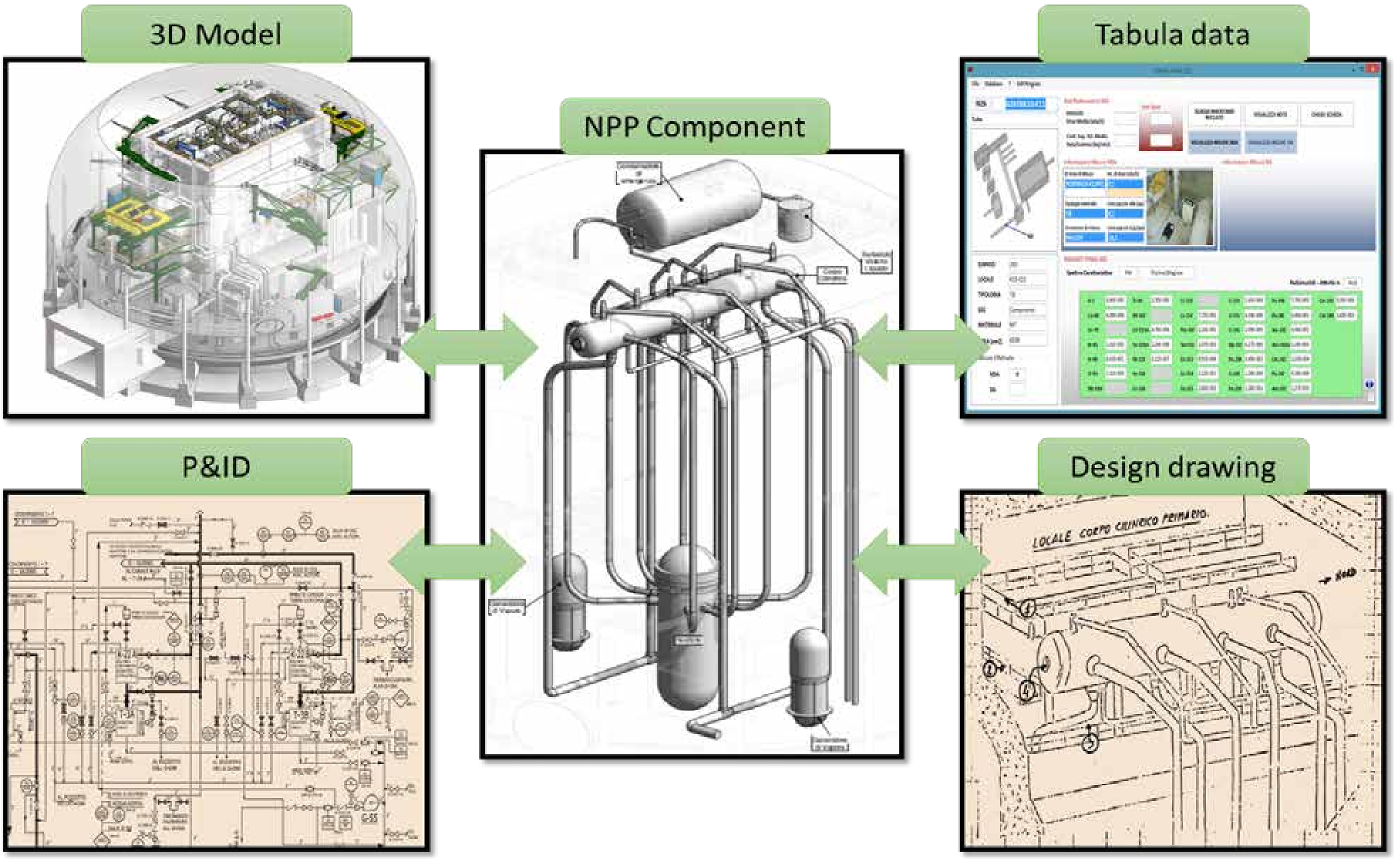

Figure 1: Example of application of K-PIM principles in a real-life NPP. Courtesy of Nucleco spa.

enough to the inspected item (because of processing items hindering the access), the omni-directionality of gamma detectors (despite eventual small shields and collimators used) and the workforce and time needed to survey a complete area/facility.

About surveillance, the need to ensure the Continuity of Knowledge (CoK) between sequential inspections is usually achieved by means of optical cameras, radiological monitors (like gamma detector and neutron counters) and other sensors (e.g., weighing devices, tank level sensors, identity reader). All these devices collect and store a continuous flow of measurements, for which adequate analysis and data interpretation is needed in order to be able to describe the (current) status of the facility they are installed in.

The goal is to obtain a model from which physical and radiological information can be retrieved and whose data is automatically integrated in the digital twin in a way it can be both visualized and quantitatively used for safeguard's goals. From a non-proliferation perspective, the possibility to combine different techniques and using multiple sensors (stand-alone or as a unique integrated device) would optimize the effort required and increase safeguard effectiveness. From the management perspective, the possibility to have a tool for creating a digital twin of the facility might dramatically improve its monitoring and future decommissioning according to the Building Information Modelling (BIM) standards.

The structure of this manuscript is as follow. Firstly, this paper introduces the possibility to use different techniques (novel techniques or techniques using technology either off-the-shelf or known to be under development) in order to create a 3-dimensional digital twin of a generic facility (with all the components within it). Then, the paper reviews the state-of-art of systems similar to the Concept, highlighting the gaps still to be filled for its future mature application in safeguards and non-proliferation.

2. The Concept: techniques and technologies involved

The goal of the proposed Concept is to (semi)automatically create a time-tracked 3D model of a certain facility including radiological information and multiple sensors data. As such, the data ensemble and the tool for visualization and data management (through a common database usually called Common Data Environment, CDE) are a direct application of BIM standard through the Knowledge-centric Plant Information Modelling (K-PIM) principles as suggested by IAEA [2] (see Figure 1). The principle of integrating different information in a model (i.e., a scene) is known as Scene Data Fusion (SDF) [3].

The Concept would consist of (at least):

- SLAM Architecture - The Simultaneous Localization And Mapping (aka SLAM [4]) engine represents the core of the Concept. This engine is needed to create the 3D model of the area of interest with its coordinate system and to determine the sensors' position within it.
- Radiation sensors – Data from those sensors can be included directly in the 3D model (but this requires the results to be fit for such visualization) or can fill a database created from the 3D model.
- Non radiation sensors – Thanks to the 3D model created by the SLAM architecture and to its capability to process the system position inside the map, many possible sensors might be introduced, as long as their output can be related to the sensor's position (known by SLAM) or can be applied to part of the 3D model. These sensors will not be discussed in this paper.

2.1 SLAM Architecture

As already mentioned, the Simultaneous Localization And Mapping (SLAM) engine represents the core of the Concept. This engine's task is to create a point cloud of a certain area or facility (example in Figure 2). The point cloud is used as a 3-dimensional representation of the area at a certain time; as such, it (and its coordinate system) can be used to spatially localize any radiological and non-radiological information that can be visualized directly on the point cloud or in an automatically built database. In the rest of this paper the Concept of point cloud and 3D model will be used as synonyms, while a clear distinction will be made when talking about parametric 3D model (like the ones created using CAD or similar tools).

The minimum hardware needed for running the SLAM engine is:

- *Sensors for point cloud acquisition,* typically a LIDAR (acquiring the point cloud with a certain frequency) coupled with an odometry camera (for determining position and pose – aka orientation – of the device inside the space). The creation of the complete facility's point cloud is performed merging all the LIDAR-acquired point clouds, guessing information about LIDAR position and pose in the space using the odometry camera and then performing a global optimization process as long as new point clouds are acquired. In order to properly complete the map, the LIDAR needs to be moved inside the space. Example of SLAM engine are Cartographer [5], RTAB-Map [6] or ORB-SLAM3 [7].

  - Point clouds can be acquired also using other devices, like laser scanners (a sort of static version of LIDAR) or using optical camera with Time-of-Flight

Figure 2: Point cloud of a Boiling Water Reactor building. Courtesy of Nucleco spa.

sensor. Changing sensors imply adapting algorithms and obtaining results with different complexity and detail level, as long as a different effort required for data acquisition and constraint to be respected. Although LIDAR are mostly used in the first system developed worldwide, at the end of the day the choice of the sensors is something that as to be performed depending upon the goal desired.

- *An on-board computational unit* able to run a dedicated operating system (a ROS – Robotic Operating System) and with enough power and storage to manage sensors data, in particular merging the point clouds acquired by LIDAR.

Regardless of the technologies used, it is important to underline that in the last years the creation of 3D model *as-built* by means of point clouds is becoming increasingly accessible, reliable, and mature thanks to the improvement in the computation power and to the possibility of using augmented reality software on common-life tools, like smartphones and tablets. Moreover, in last years the growth of computational power (e.g. parallel CPU/GPU elaboration, quantum computing), the interpretation of point cloud for object identification (and thus for automatic creation of 3D parametric models) is gaining interest in the field of Machine Learning [8] [9].

2.2 Radiation sensors

The presence of a radiation sensors package is the main feature that makes the Concept useful for safeguards and non-proliferation purposes. The underlining idea is to use versatile detectors and techniques, possibly providing outputs that can be represented and visualized. The list of the appropriate radiological sensors includes (but is not limited to):

- Gamma imaging system – The most versatile and reliable technique for this purpose nowadays. Gamma imagers, also called gamma cameras, are able to reconstruct the direction from which the recorded photons are coming. The results can be visualized directly on the point cloud, while the merging within a parametric 3D model is still to be developed.

- Neutron imaging system - This technique is less developed than gamma imaging, but the possible outcomes of its further development might be useful for safeguards and non-proliferation than this possibility needs to be discussed. The results can be visualized directly on the 3D model.

- Dose rate meter – Dose rate can be measured by dedicated sensors or by means of the detectors used for imaging. The visualization is not trivial, but the results could be included in the 3D model as a "hidden" information such as a scalar field and used to evaluate the total dose absorbed by an operator to accomplish a certain task.

- Other radiological sensors – Possible examples are the continuous air monitors. The results can be integrated into the database as part of the radiation monitoring systems. The 3D model can be used to localize the acquired data.

The world of gamma imaging systems has rapidly grown in the last decades thanks to the improvements achieved in crystals manufacturing, electronics, and algorithms. Different systems exist on the market (or as prototypes) with different characteristics, thus choosing the one to use is a decision to be made depending upon the situation [10] [11] [12] [13] [14] [15] [16] [17] [18]. However, the most mature (and probably versatile) setup sees the usage of a CdZnTe crystal (whose active volume usually ranges from 1 cm^3 up to some tens of cm^3) with segmented electronics for signal readout, using the Compton Algorithm and/or the Coded Aperture Mask algorithm for imaging reconstruction. In general, CdZnTe crystals are less efficient than NaI(Tl) and have a worse energy resolution than HPGe; nevertheless recent improvements make them much more similar to HPGe in terms of efficiency (higher crystals are possible thanks to a better management of the crystal impurity) and energy resolution (less impurity means also a better charge collection in the crystal, thus a better resolution), with the crucial advantages of being able to work at room temperature (without the HPGe annoying need to be cooled) and to permit an easy way to apply segmented electronics.

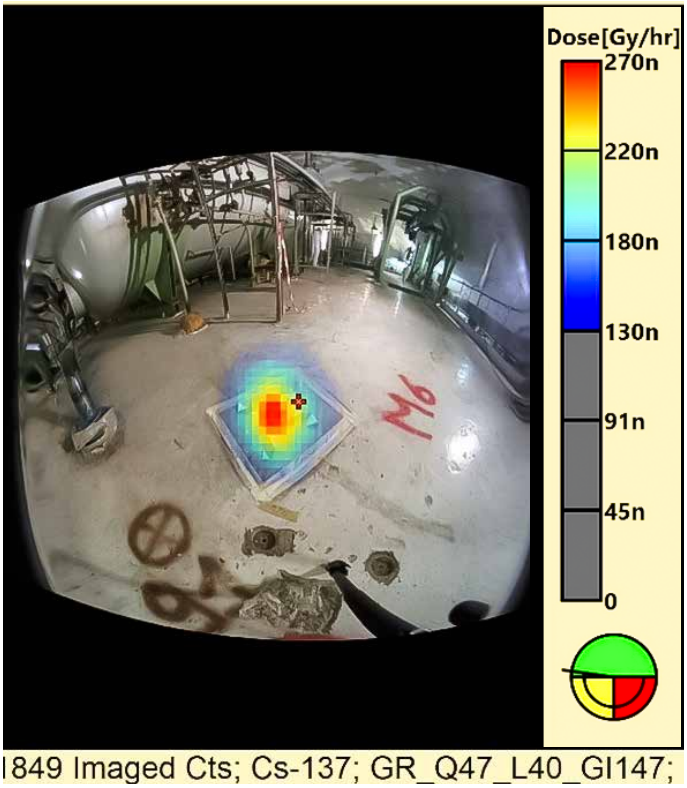

Figure 3: Example of 2D reconstruction of Cs-137 superimposed to the optical image. Courtesy of Nucleco spa.

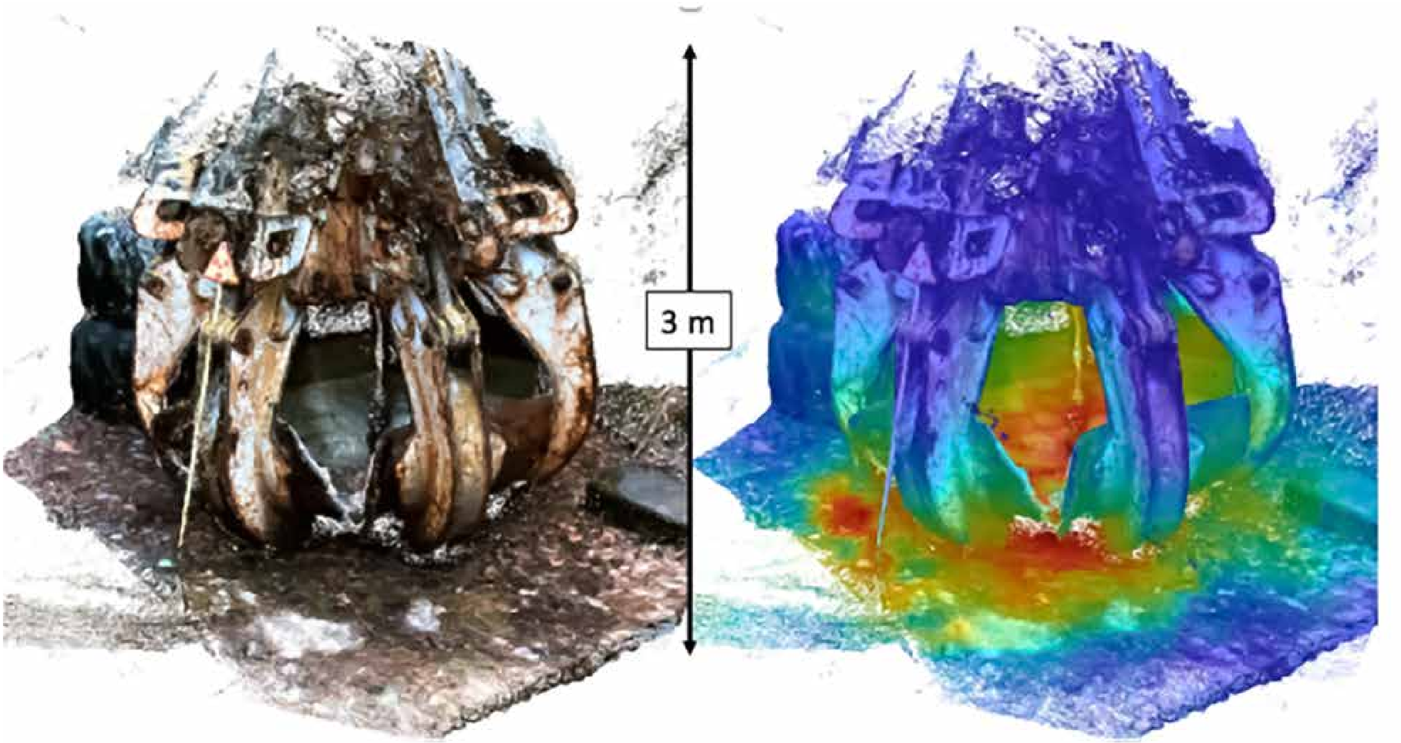

Figure 4: Photogrammetric reconstruction (left) of a claw located in forest outside Pripyat used in the aftermath of the Chernobyl accident. On the right, reconstruction of relative radiation level for Cs-137 (low level in blue, high level in orange and red) [25].

As a standalone device, gamma imaging systems typically provide the collected spectra and the 2D reconstruction of the gamma emitting radioactive material superimposed to the optical image acquired with a camera installed within the system (Figure 3). For the reconstruction, the system computes, for each recorded event, the most probable paths of the incident photons, and then sums them up in order to determine the most probable path of all the photons detected during the assay. These paths and their probabilities are exactly the data represented in Figure 3, which can thus be considered the real spatial distribution of the radioactive material emitting such photons.

The only way to reconstruct the distribution with a gamma imager without the external space physical information is using a 2D plane unless some well-known object and detector position are measured. However, the proposed Concept would allow a gamma camera to have access to SLAM data, i.e., knowing at a fixed rate its position and pose inside the 3D reconstruction of the space. This information can be used to extrapolate the probable directions for each event in a 3D space instead of a 2D plane, including corrections due to possible distance variations from the materials surrounding the system as it moves in space (see Figure 4). The information provided by the SLAM architecture permits a very appropriate evaluation of distances and interferences, being able to better distinguish among close hotspots of the same radionuclide and compute the distance-corrected quantification of the radioactivity present.

Regarding the algorithm used for computing the 3D radioactivity reconstruction, the most used is the Maximum Likelihood-Expectation Maximization (ML-EM) [19] with its variations, although it's known overfitting problems can arise and fixes are still under developments [20] [21]. However, other approaches do exist, ranging from easy-to-understand optical-like projection like the Filtered Simple Back Projection algorithm SBP [22], up to deep mathematical approaches like the Additive Point Source Localization APSL [23] [24].

In respect of just few years ago, two main improvements have been achieved by the most advanced imaging system:

- The capability to perform the imaging for a user-defined Region-Of-Interest (ROI), thus without any interference issue in imaging radionuclides having different gamma emissions (the energy resolution is crucial for this aspect).
- The capability to make quantitative evaluations of the radioactivity present. Not only CdZnTe can be used with Monte Carlo codes (like MCNP [26]), but also with point-kernel techniques for reliable radioactivity quantification [27]. Finally, the energy resolution allows the quantification of Uranium enrichment and Plutonium isotopic composition [28]. These results imply the possibility to apply a quantitative scale to the reconstruction.

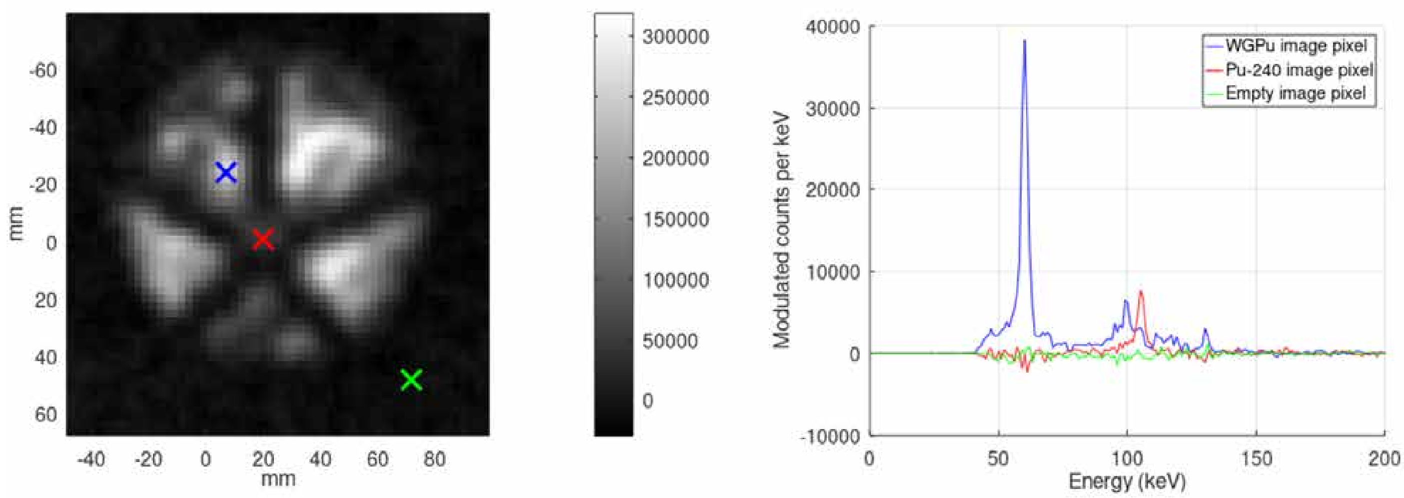

Figure 5: Example of direction spectrum: on the left, three pixels marked of a plutonium known sample, on the right the spectrum reconstructed from each marked pixel [29].

Finally, it's also to envisage the future possibility (under development [29] [30]) to retrieve directional spectra, i.e. to reconstruct (with a certain probability or fidelity) the spectrum generated by a certain hot spot emerging from a precise direction in the 3D model: this feature could potentially allow to drop the need to apply (sometime very large) collimation and shielding systems, resulting in a dramatic improvement in the imaging system versatility and operativity in standalone mode (example in Figure 5).

Regarding neutron imaging, current technology is mainly limited to using an active neutron flux to probe a certain material response [31] [32], in opposition to the passive approach used by gamma cameras. The need of an active flux is an important constraint in the application of this technique in portable devices, like the one used for in-situ inspections. However, some on-going studies (like [33] and [34]) demonstrate the possibility of performing a passive neutron imaging under certain conditions and coupling it with gamma imaging reconstruction, with results that might then be integrated into the 3D model. While waiting for this technology to be further developed, one can also use a rough neutron counter detector and apply the novacula Occami (Occam's blade) principle thanks to the SLAM-provided spatial awareness: as the neutron count rate grows when placing the counter close to an object than the object can be the source of that count rate. This approach has a simpler application and implementation but is much less precise that imaging and requires a deeper exploration of the space surrounding the item (requirement much more important for neutrons than for photons, because of their higher penetration power) in order to reduce interferences and false positives.

The dose rate can be measured by means of dedicated sensors or through the ones used for gamma/neutron imaging. Dose rate is mainly significative for radioprotection scopes (e.g., computing absorbed dose) thus it can be more important to know it in a generic point of the 3D space than at contact with contaminated/activated items and nuclear materials. This goal is often reached running complex codes and resource-demanding particle transport simulations in an as-complete-as-possible 3D model of the entire facility with (at least) all the most important hot spots included in the model. Unfortunately, this approach can be harsh to implement and make almost no sense for facilities where conditions often change. In similar cases, it can have more sense to measure the dose rate in space and interpolate the results to get an heuristic dose rate field (which can be included into the 3D model as a hidden value) to be used for any possible radioprotection scope (like in [35]).

Regarding other possible radiological sensors, generally speaking, all possible detectors might be integrated to the Concept as long as their output can be referenced within the 3D model: an example is the application of radiation-tolerant RFID technology (like in [36]) for filling radiological data to the facility Common Data Environment.

3. From the Concept to the realization: the state-of-the-art

Nowadays the proposed Concept has few working physical realizations, almost all at the prototype state (examples in [37] and [38]). The Concept's core, the SLAM architecture, is usually based upon a LIDAR (for point-cloud creation) coupled with an odometry camera (for space-awareness), whilst the radiological data acquisition relies on CZT-based gamma imaging system coupled (when possible) with a Geiger-Muller for dose-rate measurement; nevertheless, differences are present among systems, from the sensors to the algorithms used for space and radioactivity reconstruction.

Although still missing a user-friendly managing software, the system presented in [39] and [40] (see Figure 6 and

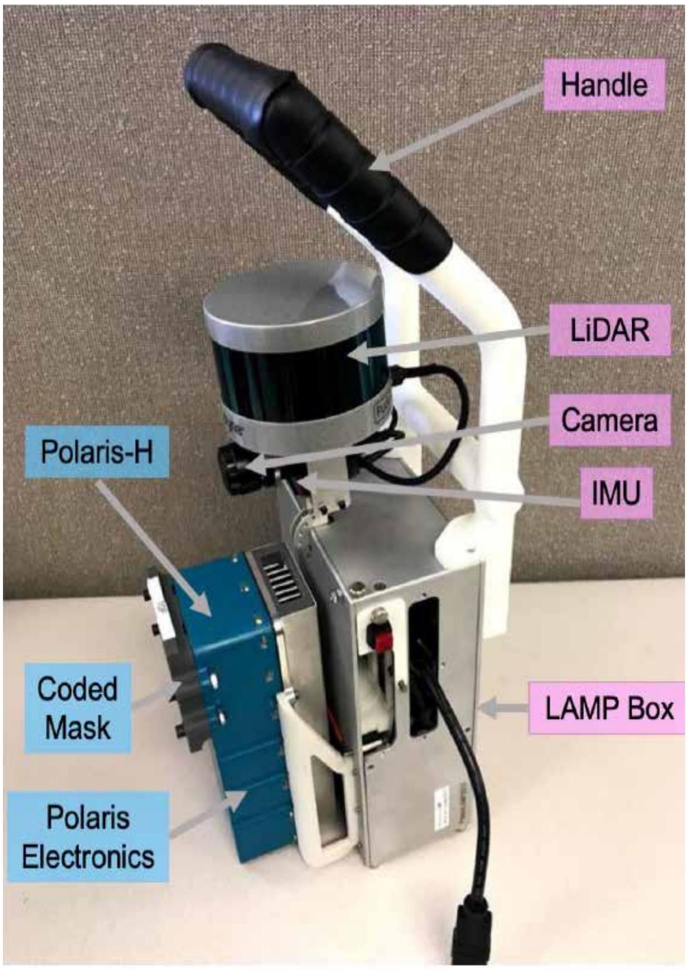

Figure 6: Polaris-LAMP system as proposed in [40]

Figure 7) appears to be most mature solution so far(in particular about the Scene Data Fusion topic), whose realization started several years ago and has reached the market recently [41]. Nevertheless, taking into account other factors, e.g. quantitative capability, managing software functionalities, computational and user effort required, the topic is far more complex and other solutions can be considered top-tiers: the system reported in [35] is equipped with an interesting software suite for radioprotection and augmented reality virtualization, whilst the system in realization reported in [42] shows enhanced quantification capabilities.

Regarding quantification capability, there are many on-going study to implement attenuation correction in the MLEM (or similar) reconstruction (which already correct for distance), thus retrieving the activity of each detected hotspot ([43][44][45]). Differently, in [42] the quantification is focused on using point-kernel based approach, similar to the world-wide-diffused commercial quantitative gamma spectrometers [46][47]. As already stated, other algorithms are under study and their application to SDF systems, like the Particle Swarming [48]. It's also worth to mention the study reported in [49] about the Minimum Detectable Activity (MDA) reached using systems like the Concept: similar evaluation would allow the user to understand the sensitivity of the assay performed as a function of the space in addition to distance (see Figure 8).

Finally, of high interest for safeguards and not proliferation is the possibility envisaged in [42] (based on previous work reported in [50]), and in [51] and [52], to apply space-aware imaging systems for 3D reconstruction and quantification in known items, in a sort of simplified (in the assumption but also in the requirement) tomography. It might be, in future, coupled with other tomographic system used for safeguards, like the PGET (Passive Gamma Emission Tomography) [53] [54].

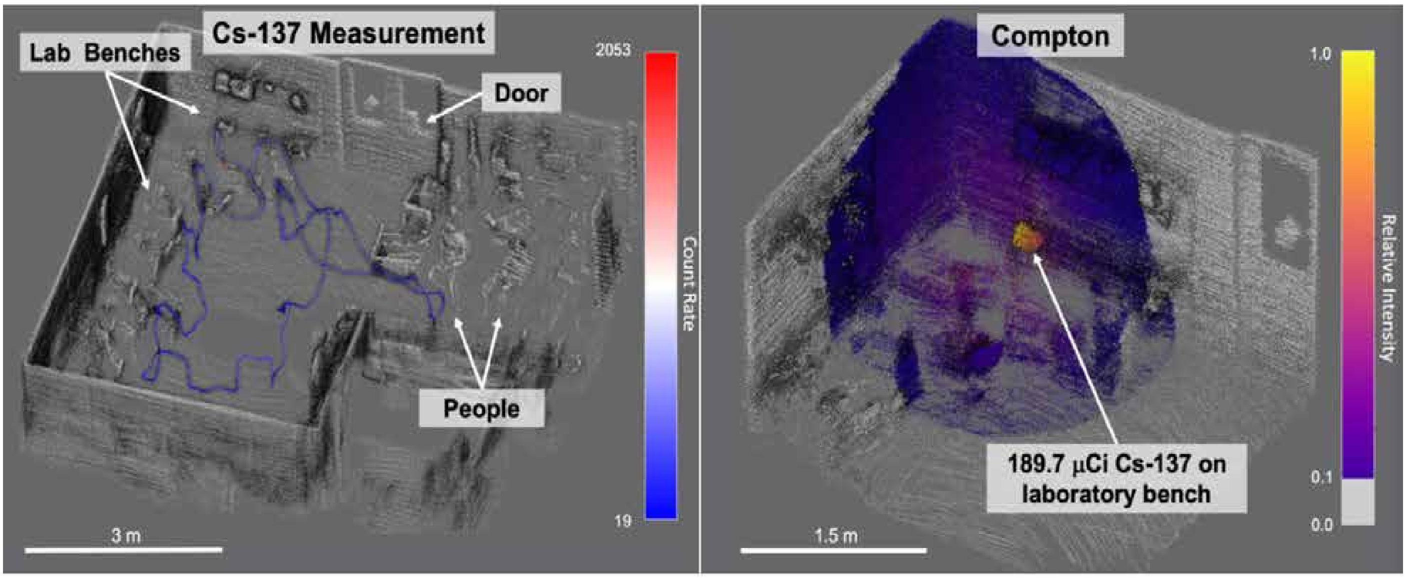

Figure 7: Application of Polaris-LAMP system: on the left, physical reconstruction of the environment with evidence of the travelled path; on the right, 3D radioactivity reconstruction using Compton Imaging [40].

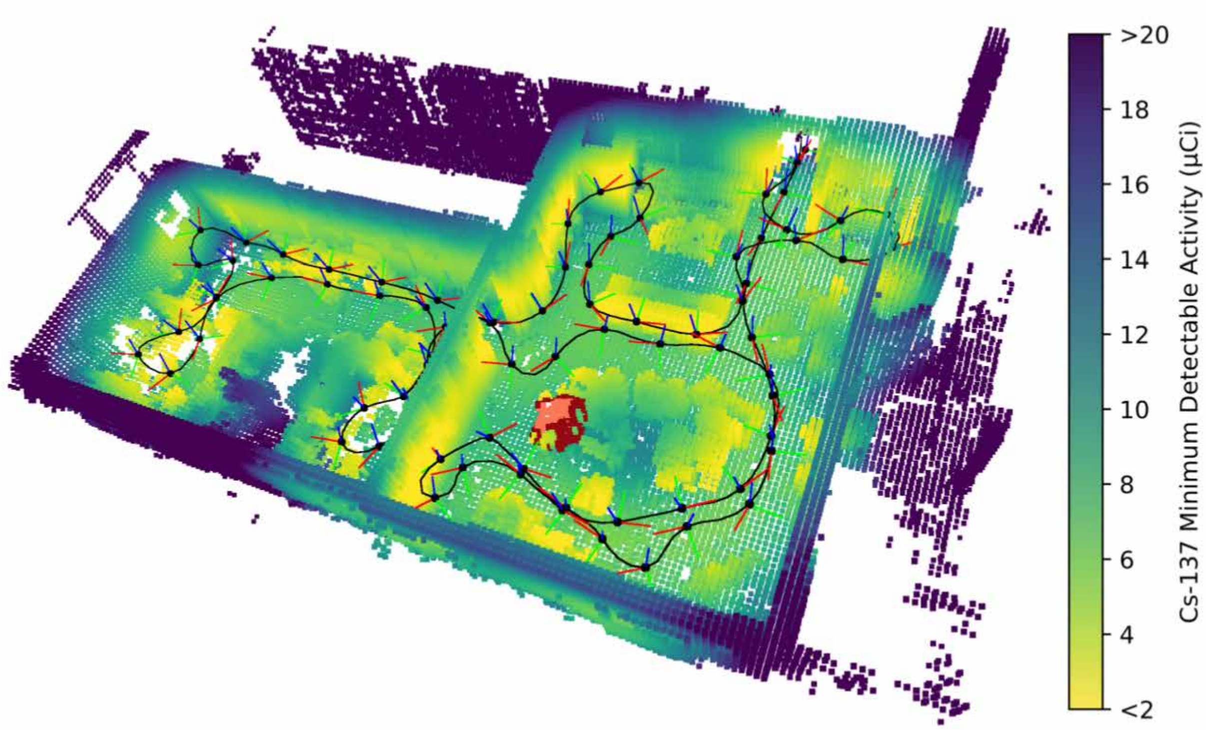

Figure 8: 3D view of MDA map for Cs-137 [49]

4. Application of the Concept to safeguards and beyond

As already mentioned, at the bare minimum the Concept will have a SLAM Architecture and a gamma imaging (capable of also evaluating the gamma dose rate). With minor effort, a neutron counter can be attached, initially without proper imaging capability. The Concept can be seen both as an integrated system or as several sensors and detectors which can be used separately for performing/optimizing specific tasks. At the present state, devices like the presented Concept are used to retrieve fast information about the position of a hot spot in a certain area, thus mainly from a radioprotection perspective.

As hand-held system, the Concept can be used to:

- Perform Design Information Verification activities, thanks to the possibility to compare the as-built 3D model from point cloud with the information declared by the user. That comparison can be extended to successive inspections to verify that nothing has changed in the facility without notification.
- During periodical inspections, to detect dose rate/gamma/neutron anomalies along the inspected installation, possible signature of SNM diverted from its scope. Thanks to the spatial awareness, the unexpected signature can be efficiently studied further with detailed measurements.

Figure 9: Example of imaging system installed on quadrupedal robotic platform during a routine assay.

- ✔ Quantify gross and partial mass defects and verify operators' declarations about Uranium enrichment, Plutonium isotopic composition, fuel burn-up and cooling time, with uncertainty similar to the one obtainable with portable HPGe.
- ✔ Collect multiple data to be used for radioprotection purposes (e.g., dose rate in air) and future radioactive waste management.

The Concept can also be used in a static mode like a monitoring system to preserve CoK between sequential inspections: during normal functioning, the system might elaborate and store the minimum data needed to identify eventual anomalies, whose detection enable the full-data acquisition. From the monitoring perspective, the Concept can be coupled to robotic systems in order to make autonomous acquisition along a pre-defined path (examples in [55] [56] [57] [58] [59]), in order to retrieve the same kind of information over time simplifying data management (Figure 9).

5. Conclusions

A Concept of an integrated system for creating 3D models and spatially aware radiological data has been introduced, reviewing what has been already developed and the improvements that the involved technologies may undergo in next future, making this kind of device of particular interest. In the perspective of safeguards and non-proliferation, the system can be seen as a multi-purpose device, whose complexity and cost are justified by the large amount of information obtainable without the need of other tools: in fact, it can be used not only for inspections, but also as (part of a) monitoring system and as a tool to keep track of spatially-aware and time-correlated physical and radiological quantities inside the facility, in order to complete its K-PIM description according to IAEA indications and preserve the Continuity of Knowledge.

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