Examining Autonomous Inspection of Geologic Repositories

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Abstract

Geological repositories for nuclear waste, including spent nuclear fuel, present a significant challenge for traditional International Atomic Energy Agency (IAEA) safeguards tools due to their inaccessibility and demanding operational conditions. The IAEA has been working closely with Member State organizations currently involved in repository construction and planning including Euratom, the Finnish and Swedish regulatory authorities, and relevant facility operators. A verification challenge for the IAEA is to verify that no nuclear material is diverted from a repository environment. The challenge is also not static as activities must encompass verification of the design prior to and during the construction/operation phase, and post backfill. Throughout these various phases, it is imperative that the IAEA maintains a continuity of knowledge (CoK) of all material, including information on material inventory and flow. Monitoring via autonomous robotic vehicles may augment current and envisioned IAEA safeguards approaches for geologic repositories. Implementing automated solutions for underground nuclear repository inspection may be a new venture for the IAEA but carries the potential to greatly enhance the efficacy and efficiency of inspections and allow inspectors' time and expertise to be directed where needed most. This paper highlights these challenges and outlines how they might be addressed by using remote or autonomous vehicles. Specifically, it discusses the current state of the art in robotic autonomy for known or partially known environment mapping and patrolling, as well as shared autonomy, where humans collaborate with closed loop autonomation to complete tasks. The feasibility of using rovers for these verification tasks is explored, along with the challenges associated with system implementation. Hardware and software suggestions are provided based on the adoption of similar technologies in other comparable areas and ability to close technical gaps. Lastly, human-robotic interactions are considered based on the challenges of the environment of the repository and effective deployment and continued operation of the robot system.

Keywords: Geologic Repository, Autonomous Monitoring.

1. Introduction

This paper explores possible robotic technologies to aid and augment IAEA inspection of deep geological repositories. The identified technologies can help maintain continuity of knowledge (CoK) of spent fuel stored in buried canisters during the repository's operation phase. The functional lifecycle of a repository will transition through several phases: pre-operation, operation phase, and post-operation. The pre-operation phase involves geological assessment of a spent fuel repository site. The operation phase, the focus of this paper, is the most complex and involves the construction, processing, emplacement, and backfill of canisters containing spent fuel. The post-operation phase addresses closure of the facility and the long-term monitoring and maintenance. The KBS-3 repository is currently at various stages of development and use in Sweden and Finland [1] and its design, based on the KBS-3 method developed by SKB, is further along than any other repository. It will serve as the model repository template for this paper, although the technological evaluation and applicability of the approach are not limited to this particular repository design.

Given that the design and construction of future deep geological repositories will occur over many decades and in a multitude of countries and geological regions, the potential for variability of repository designs is quite likely. These variations coupled with limitations for routine inspector-access and the complications posed by continual State activities occurring within and requiring access to the repository during the operation phase create significant challenges to traditional safeguards solutions for maintaining CoK over spent fuel. During the operation phase, the repository consists of a surface facility (above-ground) and a sub-surface facility (below-ground). The surface facility can serve a variety of functions by simply acting as an entrance to the sub-surface facility, housing an encapsulation plant, and offering temporary storage before emplacement. Due to the accessibility that IAEA inspectors now have to the above-ground facilities, this paper will not focus on technologies to help augment or automate above-ground inspection processes; rather, it will focus on maintaining CoK over the spent fuel in the sub-surface portion of the repository. However, solutions highlighted in this paper may apply to

 Benz, J., Palmer, C., McGee-Hilbert, H., Lee, C.Y.H., Kumar, R., Hollinger, G., & Benker, N.(2022, June). Examining Autonomous Inspection of Geologic Repositories. ESARDA Bulletin - The International Journal of Nuclear Safeguards and Non-proliferation, 64(1), 48-63. https://doi.org/10.3011/ ESARDA.IJNSNP.2022.5

above-ground challenges such as temporary storage of encapsulated spent fuel.

This paper is the result of a research collaboration between Pacific Northwest National Laboratory and Oregon State University, supported by the U.S. National Nuclear Security Administration's Office of International Nuclear Safeguards. The research explores two aspects of autonomous monitoring critical to identify a feasible deep geologic repository monitoring solution: 1) the level of autonomy of the robotic inspection vehicle; 2) potential technologies which have been, or can be, demonstrated as usable in the challenging repository environment. The following sections provide a high-level introduction to the KBS-3 design, discuss differing degrees of autonomy and potential monitoring technologies, and conclude with example robotic inspection systems that could be evaluated for future use in safeguards applications.

2. The KBS-3 System

A typical KBS-3 repository system in operation phase consists of underground openings, nuclear waste canisters, buffers, backfill, and engineered barriers, as seen in Figure 1. According to the KBS-3 production report, construction of additional drifts in the underground sections can all occur concurrently during the operation phase of the nuclear waste facility [1]. A brief summary of the construction process is provided in section 2.1 to provide context for the environments in which the robot systems would operate and to highlight the applicability of the suggested monitoring automation technology; more detailed information is contained in KBS-3 reports [2, 3].

2.1 Repository Construction

The model KBS-3 repository is located deep within bedrock and accessible only through access tunnels and shafts which lead to disposition tunnels, each housing multiple holes or cavities along its length. The spent fuel is encapsulated in copper canisters, described in more detail in Section 2.2, and emplaced in the cavities. Bentonite clay is packed around the canisters and the tunnels are backfilled and plugged to stabilize the sealing. This also prevents access to the canisters. Once the tunnels and shafts are filled, the repository will be closed. The IAEA safety standard SSR-5 gives the safety requirements, the passive safety must be demonstrated but no monitoring shall be left beyond the plug. might be referred here

While the repository is in the operational phase, it is assumed that there will be many tunnels in different stages; construction will continue for portions of the repository

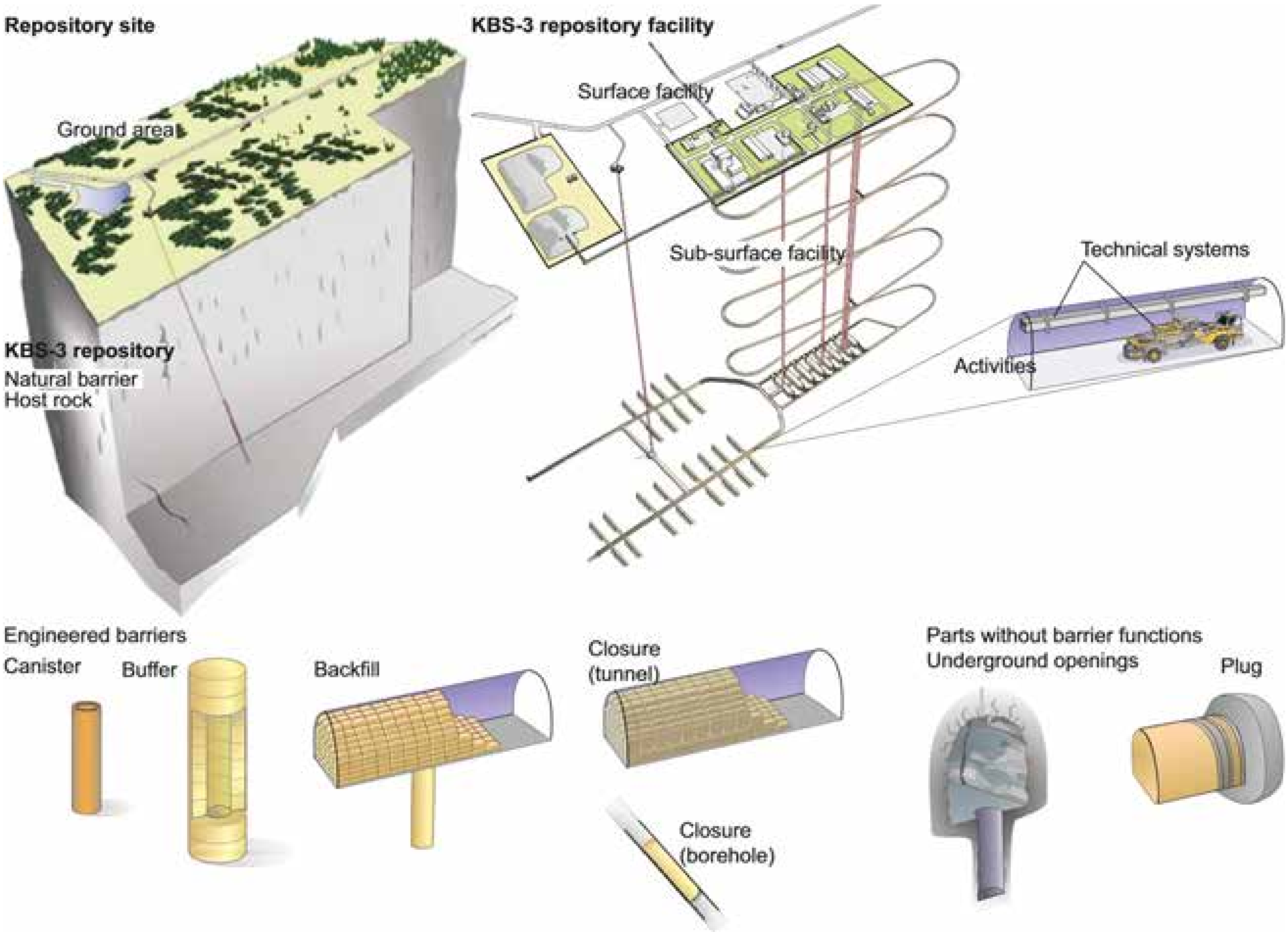

Figure 1: CKBS-3 repository layout [1]

while emplacement and backfill occur in others. As a result, the underground facility will be constantly evolving and it will be important to monitor changes in order to detect whether any undeclared activities of concern have occurred, such as the removal of backfill material or excavation in unauthorized locations, as these activities could indicate attempts to divert previously emplaced material. The emplacement process itself is also valuable to monitor to provide independent assurance that a canister was emplaced in the declared location.

2.2 Spent Fuel Canister

The KBS-3 methodology uses a spent fuel canister design that involves a corrosion-resistant copper shell that encapsulates the spent nuclear fuel assemblies placed in steel-iron internal. The canisteris designed to withstand corrosion and mechanical loads anticipated from the surrounding bedrock. Although the canister is designed to accommodate multiple fuel assemblies, safety considerations related to long-term storage of the waste canister inside the repository impose limits on the maximum decay power and radioactivity at the canister's surface – subsequently limiting the number of fuel assemblies allowed. The burn-up and age of the spent fuel assembly inform the calculation of the radioactivity and decay heat of the fuel assembly which governs the number of fuel assemblies that can be encapsulated within a single canister. The KBS-3 canister has specific guidelines for the acceptable decay power and radioactivity at the canister surface, such as:

- Maximum permissible decay power: The KBS-3 safety guidelines explicitly state that the total decay power in each canister should not exceed 1,700W [1]. This limitation should maintain the temperature in the buffer less than 100°C. Temperatures exceeding this value may have adverse impacts on the properties of the engineered barriers and the surrounding rock.
- Radiation dose rate: Similarly, the radiation dose rate at the surface of the canister must be less than 1Gy/h as high radiation levels may lead to the formation of nitric acid and other corrosive species at the canister surface [4].

The canister is deemed ready to be emplaced in the repository once these safety conditions are met.

3. Levels of Autonomy

Autonomous robotics is currently a research topic which is drawing a lot of attention. The field of study delves into various aspects of autonomy such as autonomous mining, unknown environment navigation, task allocation and scheduling, robotic localization, path planning, and multi-robot coordination. A robotic rover can augment in-person/onsite IAEA inspections of the geological waste repositories by providing inspectors with an extension of sensing capabilities to areas that might otherwise be challenging to access on a regular basis. Some key aspects of rover design and deployment that should be explored are the automation capabilities that allow it to maneuver around the repository environment.

Three levels of automation are discussed in this paper, which could be used for inspection implementation: full autonomy, shared autonomy, and manual teleoperation. The advantages and disadvantages of each, as well as the considerations for state-of-the-art automation implementation, are discussed and described within this section. The feasibility of each approach for IAEA inspection tasks will depend on external factors such as inspection timelines, repository environment, budget, and technological availability and future research is encouraged to fully evaluate their applicability to safeguards objectives. Beyond the scope of this paper, but of relevance to a viable solution, is the inclusion of Euratom where many repositories will be located. Here, implementation of solutions should be considered, as all safeguards equipment must be authorized for common use across Euratom authority.

3.1 Full Autonomy

Fully autonomous operations encapsulate the common perception of robotics—where a robot can self-maneuver and accomplish tasks with minimal to no human intervention. In practice, this requires a large amount of research and development to implement a truly hands-off system. A fully autonomous system can allow an IAEA inspector to deploy several robot systems at once to complete the inspection without overloading the attention capabilities of the inspector. In the case of remote inspection implementation, multiple systems can be deployed at once with the operator simply monitoring the status of each robotic system. This can provide improvements in efficiency over current inspection techniques, especially in those locations where access poses great risk to human inspectors.

This paper discusses potential situations where fully autonomous capabilities may be generally applied to IAEA inspection methods for underground waste repositories, but further detailed research specific to each repository is recommended. Exploration of unknown environments requires algorithmic solutions that process sensor information (e.g., LiDAR scans, camera images) and return a direction of desired travel. Even with the declared ground-truth information of repository design layouts, construction deviations and potentially undocumented drifts may be present which require impromptu assessment and decision-making approaches.

A popular method, frontier-based exploration algorithms, has proven successful and has been commonly applied in the robotics community [5, 6, 7, 8]. Another example solution would be to apply task allocation and scheduling to organize sub-objectives alongside the main objective of nuclear inspection. The deployed system would be capable of navigation through the environment and may encounter a variety of sub-tasks such as plug inspection scheduling or deposition hole verification [9]. Desired mission outcomes would be programmed beforehand by the operators and algorithms would have to balance operational parameters (e.g., remaining mission duration time and power supply), with inspection goals (i.e., confirming integrity of drift closure versus canister ID and integrity verification in deposition hole) in order to determine which sub-tasks to perform.

The final example considers the case where multiple robot rovers may be deployed simultaneously into the underground repository to maximize the area covered in a single excursion. These robots would require scheduling and coordination between units to optimize efficiency in addressing competing inspection goals [10, 11]. Additionally, this kind of multi-robot coordination would need to consider scenarios in which communication disruptions could occur between one or more units, requiring contingencies to allow each unit to adapt to such situations and make plan adjustments in a decentralized manner [12, 13].

3.2 Shared Autonomy

Shared autonomous operation can incorporate desirable elements from fully autonomous or manual approaches in a modular fashion, without the level of painstaking development required for full automation, and with less demand on operators than required by manual teleoperation. This approach allows situational adaptability, at the cost of certain capabilities. Furthermore, a shared autonomous solution can be implemented as a developmental midpoint between a manual and fully autonomous approach, with incremental features developed, tested, and implemented at separate times.

In addition to research topics for fully autonomous robotics, shared autonomy research topics include fields like human-robotic collaboration and hybrid control schemes. In the case of nuclear repository inspection, an example of human-robot collaboration could be graphical user interface (GUI) control designs to help maximize the productivity of the IAEA inspector without overloading them with inspection results and data. Additionally, verification technologies return information in different forms, such as radiation measurement spectra or images indicating the quality of deposition tunnel backfill. The inspectors' data needs can be studied, and the display options modified for desired traits, output, and controls, directing the inspectors' attention where it will be most effective [14, 15].

An example of a shared autonomous application can involve navigational waypoints with task commands issued to a unit by the inspector. The unit may then execute the commands in an autonomous fashion, or revert to manual teleoperation for more complex, sensitive, or difficult tasks. Additionally, autonomous sub-routines may be installed for the robot to take independent action if communication with the operator is lost. These routines could be as simple as performing recovery behaviors like backtracking to the last known position within communication range or reinitializing communications channels, or extended behaviors to enable the inspection of areas of interest that fall outside of communication range, such as the exploration of undeclared tunnels or sections. In both instances, the successful execution of the sub-routines will return the robot to a location within communication range, allowing the operator to resume manual teleoperation.

Understanding and developing the human-robotic collaboration will necessitate the creation and use of control systems to allow inspectors to interface with a unit during planning activities, navigation, movement, and task execution. A control system must allow for smooth shifting between levels of autonomous function and operator control; for example, when an inspector observes an area of interest, they must be able to designate tasks for the robot to execute which allow for closer inspection. This alternation between autonomous self-guidance and manual control can require a flexible control scheme which is capable of many modes of operation and a variety of input types [16].

3.3 Manual Teleoperation

Lastly, manual robotic teleoperation has been demonstrated to be fully viable in a variety of high consequence applications [17]. In this operation mode, the inspector has full and direct control of the robot's motions and planning capabilities. An example of manual teleoperation would involve an inspector at the base station sending motion commands to a unit based upon feedback obtained through the unit's onboard sensors. This base station can be either on-site at the geologic repository or remote from another location, provided constant communication is maintained.

The teleoperation option is the easiest to implement based on current developments in technology, however, the efficiency of this option is much lower than that of other options. The performance of the system is highly dependent upon communication quality between the inspector and the rover. It also requires substantially more inspector training and full attention of the inspector at all times during operation. Furthermore, this limits an inspector's ability to deploy multiple units at once. Practical implementation of this technology may require a permanent communication network to be deployed along the main and deposition tunnels within the underground facilities, which would need to be expanded as construction progresses. Another option for implementation could utilize a temporary communication network, consisting of retrievable communication nodes placed by the unit as it travels along the inspection path [18, 19].

4. Autonomous Technologies for Verification of Geologic Repositories

This section introduces sensor and robotic technologies which could be employed by IAEA inspectors to maintain CoK of spent fuel in geological repositories. Robotics have been utilized in environments like underground repositories for goals such as inspection, search and rescue, and exploration [16]. There is active development, including government-funded efforts, in progressing the capabilities of autonomous robotics [20]. The authors recognize that there is ongoing research being performed in this area and related to some of the technologies listed below, by IAEA member countries. For a few key examples, please see [70 – 76].

4.1 Robot Sensing Technologies

The verification technologies recommended for implementation on autonomous robots require general considerations of portability, power consumption, current state-of-the-art, and the ability to augment IAEA inspection. The verification technologies are targeted towards implicit and indirect inspection techniques to maintain CoK since most of the sub-surface portion of the operation phase does not involve direct access or visual line-of-sight to the spent fuel canisters.

4.1.1 LiDAR Mapping

Large-scale mapping of complex environments has been effectively accomplished by long range light detection and ranging (LiDAR) sensors and point cloud methods for a variety of uses. LiDAR has been applied in underground mine environments like those proposed for deep geological repositories [21], and the Joint Research Centre recently employed the use of backpack mounted LiDAR for IAEA usage in nuclear facility design information verifications (DIV) [22].

The integration of these use cases with robotic rovers can provide a means to address IAEA DIV safeguards criteria for geological repositories during construction and operation stages. The LIDAR technology can be mounted on a mobile robot and combined with odometry information to create detailed digital maps which can be compared to reference facility designs during each routine inspection.

Figure 2: Velodyne LiDAR Puck [23]

LiDAR hardware is commercially available and widely supported. This sensing technology benefits from a large market and wide variety of applications. There are multiple hardware manufacturers (e.g., Velodyne, Waymo, Sick) who also provide commercial off-the-shelf software to fuse the data together from different viewpoints. An example of a commercial Velodyne LiDAR Puck is shown in Figure 2. For robotic integration, there may be more specific work necessary to integrate the LiDAR information with odometry information. Simultaneous Localization and Mapping (SLAM) algorithms are commonly used in robotic applications to combine the data streams to provide real time maps and floor plans [24]. An example of SLAM is shown in Figure 3.

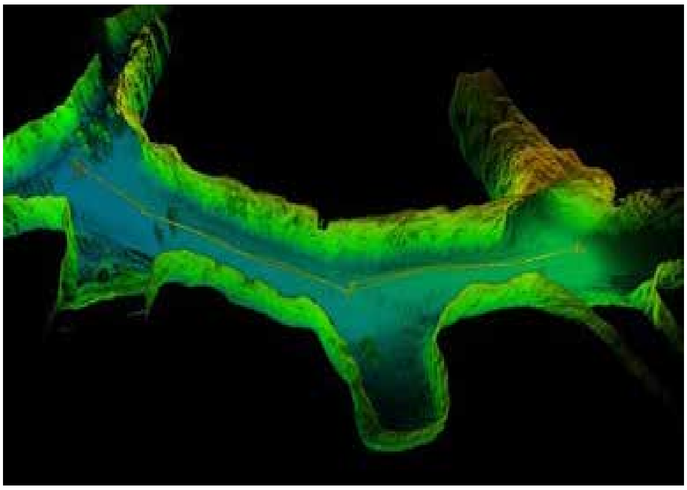

Figure 3: Map of underground mine created using LiDAR and a robot [25]

4.1.2 Optical Imaging

Alongside long-range perception capabilities like LiDAR, short range feature identifications can also support inspection routines through change detection capabilities. Optical camera sensors can be an option for short range analysis of defects or disturbances to different features of the geological repositories. These sensors have a shorter sensing range compared to the LiDAR scanning systems but have increased resolution and optical distinguishing capabilities (i.e., red, green, blue (RGB) color models). A commercial example of a RGB-D (color + depth) camera is shown in Figure 4. As a potential capability, such a camera can be used to visually inspect the surface of a bentonite plug at the end of a deposition tunnel and compare it with past image data to ensure no deviations or disturbances, in both its placement and appearance, are present. Feature-based identification methods are also available and image recognition of defects and surface cavities can be conducted during inspections.

Figure 4: Intel Realsense D435i RGBD Camera [26]

Like LiDAR, imaging technology is readily available and is supported in a variety of industries. A few examples of camera sensor manufacturers are Intel, Sick, and Keyence. Much of the novel implementation for this application would be in software development. While image displaying software can be configured off-the-shelf with little effort, machine vision and recognition software will likely be required for more intensive inspection tasks, such as plug inspection and backfill surface disturbance validation, and may require more customization. Algorithms like Scale-Invariant Feature Transform (SIFT) have been used readily in applications which require image feature comparisons [27, 28]. In a KBS-3 plug imaging example, these algorithms can be used during each inspection to compare against the images taken at the time of plug installation. Research will need to be conducted to establish disturbance and deviation thresholds of image matching scores for IAEA safeguards baselines.

4.1.3 RFI On Metal Tagging

Traditionally, radio-frequency identification (RFID) tags are used to uniquely identify objects. Tags are attached to an object and later identified with the help of an electronic reader or interrogator. RFID systems have an integrated circuit and a transponder that communicates to an RFID interrogator through radio waves. However, traditional RFID tags may not be applicable in a subsurface repository since canisters like the KBS-3 are made of copper, and the depth of the buffer layer may prove to be a barrier for the communication between the transponder and interrogator. This challenge is due to the higher frequency of traditional RFID tags and readers which are severely attenuated in these types of environments. A potential solution is a magnetic alternative to RFID, RFID-on-metal, which uses a packet-based wireless technology. For example, the IEEE1902.1, or RuBee, is an RFID-on-metal tagging protocol that is accurate even when attached to a metal surface [29]. The RuBee tag's wireless signal has been shown to travel through solid materials [30] and even works when embedded inside a steel plate, as shown in Figure 5.

The integration of an RFID reader suitable for the detection of an RFID tag with a robot system can be accomplished [31] and could be used to verify the continued presence or movement of material within a repository, particularly before any back-fill activity is initiated. As the RuBee's communication protocol is based on magnetic field waves [32], the low frequency and long wavelength characteristics might be suitable for transmission through both the bentonite clay and copper canister in which spent nuclear fuel is encapsulated.

RuBee comes with a long battery life of more than 15-25 years [32], which supports monitoring during the operational phase of KBS-3 better than normal RFID tags [33]. Additionally, since RuBee communicates at a low frequency of 131KHz and has low power characteristics, it is an attractive technology for operation in harsh environments on or near steel. As shown in Figure 6, RuBee tag has even been demonstrated to be able to communicate through stainless-steel, something that many other RFID solutions cannot do [32]. If RuBee is left in place for ultimate disposal, it would be important to evaluate the long-term risk to canisters in proximity to RuBee, or other types of RFID.

4.1.4 Ground Penetrating Radar Systems

Ground-penetrating radar (GPR) is a non-destructive geophysical technique to investigate the underground surface. This method can provide a high resolution 3-D subsurface

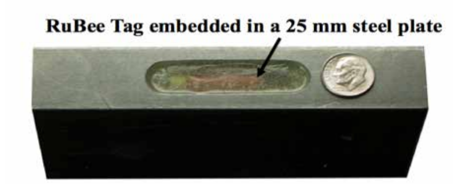

Figure 5: Embedded RuBee Tag inside steel plate

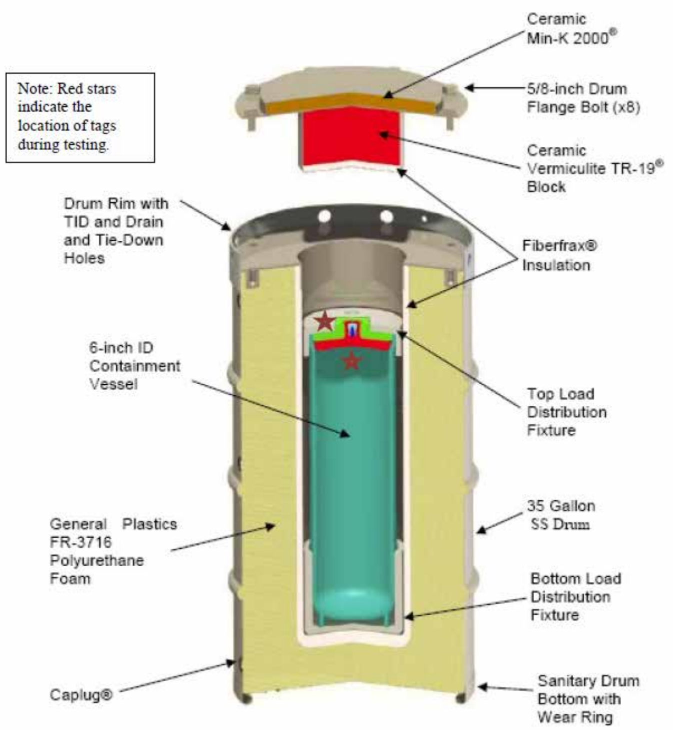

Figure 6: RuBee Tag inside US-DOE certified Type-B Model 9977 drum

image using radar pulses in the microwave band of the radio spectrum. For the creation of a subsurface image, a radar pulse is transmitted through the surface material, and the strength and time of reflected signals are recorded (Figure 7). Reflections are produced based on the electrical conduction properties and dielectric permittivity of the material from which they occur. Metals act as a complete reflector and thus do not allow any amount of signal to pass through. The frequency of the radar pulse could be optimized to the reflective characteristic of the buffer material. If an area is to be scanned, then a series of pulses will be sent throughout the surface [34].

This subsurface imaging capability of ground-penetrating radars is actively utilized to detect metallic landmines buried in the ground [35]. For the KBS-3 repository design, the spent fuel canister is to be emplaced inside the bentonite buffer. Therefore, GPR technology could be used to verify the continued presence of the canister emplaced under the buffer surface due to the electrical conduction properties and dielectric permittivity difference between bentonite clay and copper canister. Challenges exist which would need to be understood prior to use, including the structure and formation of the repository strata to allow for appropriate analysis of GPR results.

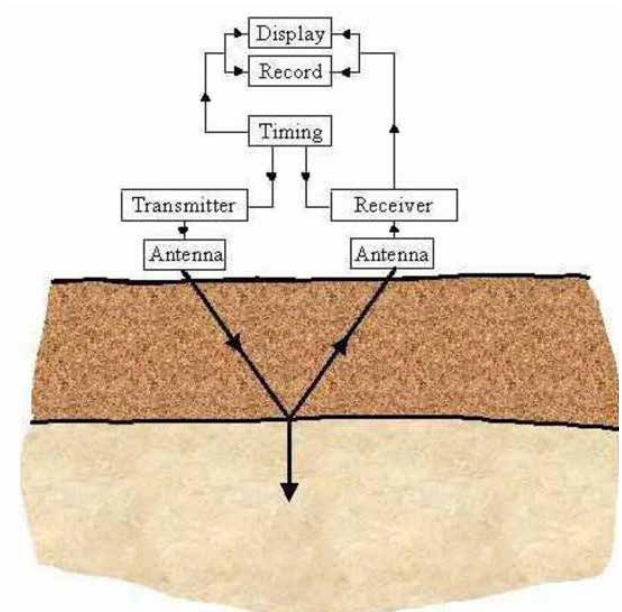

Figure 7: Working principle of GPR [36]

GPR systems are available commercially from various manufacturers such as Geophysical Survey Systems Inc. (GSSI) and GeoSearches Inc., among others. The relative simplicity of the GPR system allows for easy installation on a robot rover system [37, 38]. For instance, CRUX-GPR was developed by the NASA JPL for the “Construction and resource utilization explorer” (CRUX) project. This CRUX-GPR was also mounted under the chassis on the K10 “Black” robot system for underground mapping, as illustrated above in Figure 8 [37]. To maneuver a rover mounted with GPR inside a deposition tunnel, the system will need a control unit to operate subordinate components and signal processing, a display unit to generate a cross-sectional profile for the scanned area, and a continuous power supply [39].

Figure 8: K10 “Black” CRUX GPR [33]

GPR technology could be an attractive option for inspection activities at an underground repository since it provides a continuous real-time cross-sectional profile without drilling or digging beyond the surface. Also, it can detect unspecified underground voids and trenches in the repository which, apart from surveillance activities, would be useful for exploring the buffer material or host geology beyond the surface. It is operable across a considerable range of frequencies (1MHz-5GHz) depending on the competing requirements of resolution and depth of penetration, allowing for optimization of use case. Potential challenges associated with operating GPR in an underground repository may include power system requirements and maneuverability. Ultimately, the method still needs validation under realistic conditions before GPR can be realized for autonomous monitoring purposes.

4.1.5 Measurement and Detection of Radioactivity

It is expected that IAEA inspectors will perform a series of non-destructive analysis (NDA) measurements on the spent fuel at the above-ground facility. If desired, after a canister is emplaced, NDA measures could also be used to maintain CoK of material in the canister. Passive NDA technologies for gamma-ray and neutron measurement are widely available from many commercial vendors and can be successfully integrated into robotic systems. For example, a radiation detecting robot system mounted with a Geiger counter, camera, LCD screen, and Xbee modems controlled by an Arduino microcontroller has been used to travel through and characterize highly radioactive areas [40].

It is unlikely that a high-resolution detector such as high purity germanium (HPGe) would be viable for use on an autonomous unit. More realistic solutions could be gamma detection techniques for gross counting using a Geiger counter or spectroscopy using a low-resolution sodium iodide (NaI) detector or a medium-resolution cadmium zinc telluride (CZT) detector. Alternatively, small neutron detectors (e.g., He-3, BF3, or Li-6 and ZnS(Ag)) could be deployed. One benefit of small neutron detectors over gamma systems is that neutron detection may help differentiate special nuclear material from other benign or nuisance sources and would not rely on spectroscopy.

Significant questions remain about the feasibility of using passive NDA techniques. Although it is the most direct method to establish the integrity of nuclear material inside a waste canister, one disadvantage is that the post emplacement radiation signature is likely to be reduced to very low levels due to the sheer volume of surrounding material. For example, if a nuclear material that emits 662 keV gamma rays is surrounded by 70 cm of buffer material (polyvinyl polymer-coated bentonite clay with a density of 2.8 g/cc) then the gamma-ray signal will be attenuated by at least a factor of 108 [41]. Computational models based on modern radiation transport codes such as MCNP [42] can be used to assess the impact of the attenuation of the encapsulation on the radiation signature of spent fuel and confirm the viability of this approach for maintaining CoK.

4.1.6 Temperature Profile Measurement

A thermographic camera can detect infrared radiation wavelengths as long as 14,000 nm [43] which are emitted by an object. An example thermal image is shown in Figure 9. Like a characteristic radiation signature, the decay power (heat) of a fuel assembly depends on its burn-up, age, and mass of radioactive material, which can be estimated using SCALE/ORIGEN or other similar software packages. With knowledge of the decay heat source term of the emplaced material, the temperature in the buffer region of the repository can be estimated using modeling and simulation software such as ANSYS [44]. Inspectors can combine computer modelling and thermal detection measurements with qualitative material accountancy techniques during inspections on emplaced material. In this type of measurement, the expected temperature at the buffer's surface (based on computer modelling) would be compared with the actual measured temperature to determine whether a heat source is present. Although this measurement cannot confirm the presence of radioactive material, the approach would serve as a consistency check and could add a degree of confidence in the CoK for the emplaced spent fuel canister, in place of or in complement to using NDA techniques if so desired. In both cases, measurements are only available for the time window before the emplacement tunnel is filled in.

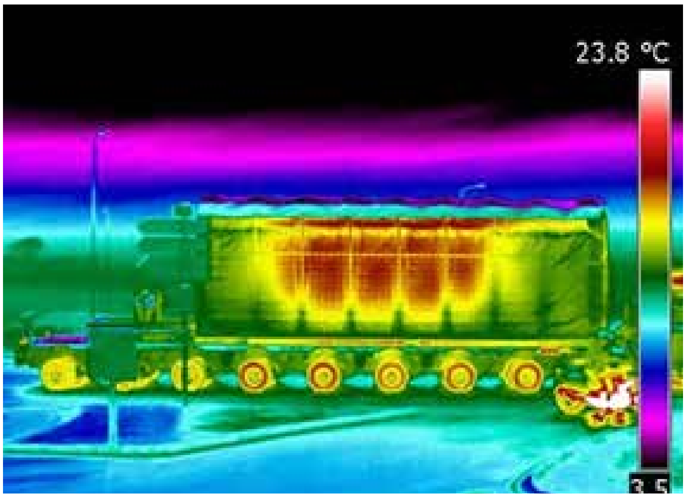

Figure 9: Thermal image of railcar CASTOR system [45]

5. Technology Implementation Considerations

This section addresses considerations in combining available sensor technologies with operations aided by automation within the levels outlined in Section 3 to fulfill safeguards requirements.

5.1 Robot-Assisted Inspection System Design Considerations

An inspection system using any level of remote inspection capability is assumed to be designed and tailored to the IAEA inspection process. Environmental variations between repositories will require flexibility in dealing with facility-specific challenges and an effective inspection system must be facility-agnostic. Solutions specifically tailored to inspection (rather than the needs of another industry) would better allow for system expansion, including accommodation of future sensor designs and modifications to inspection tasks. Current commercial-off-the-shelf underground and mining inspection equipment may provide a framework for inspection solutions but would need to be adapted to suit mission needs. Units must be resistant to environmental elements like water and dust, be capable of traversing rocky terrain with obstacles, and potentially communicate in a bandwidth-restricting environment. Notably, any custom modification, adaptation, or integration of equipment developed for other environments would require operational tests to ascertain equipment suitability and reliability for inspection requirements, safety for operation in inspection environments, system power performance, and operational longevity. Additionally, data security, and hardware and software integrity must be provided for in any solution. The former could be achieved through data authentication, while the latter through tamper indicating enclosures and/or conduits.

The following discussion of automated inspection systems for safeguards use in geologic repositories is derived from currently available robots which operate in similar environments [46, 47, 48], thereby supporting the selected specifications. Focus is placed on hardware considerations, as opposed to software, because much existing hardware is currently available which could be adapted for use. However, from the software perspective, it is unlikely that an entire software stack would need to be written, as many packaged algorithms available could be adapted and integrated to serve as the basis for this system, though customized software development for this novel robotics application will be required. The creation of full or shared autonomy software is still part of on-going research and development and extensive testing would be needed once the initial software development is completed.

5.1.1 Baseline Hardware

Baseline hardware can be divided into three major subsystems: motion hardware, electronic and computing devices, and power supplies.

Motion hardware includes a unit's chassis, motor controllers, actuators, and locomotion hardware (e.g., wheels, treads, etc.) it uses to move through a space and manipulate objects. Motion hardware must contain protections from the physical environment, and supply effective locomotion, whether a unit uses wheels, continuous tracks, treads, or Mecanum wheels (which allow omni-directional movement). Ultimate selection depends on facility and environmental requirements. Higher complexity motion hardware may make maintenance tasks more difficult or more frequent, and may result in difficulties with uneven terrain, resulting in operational delays or failures. Motion hardware will also likely constitute much of the unit's weight, having a significant impact on power requirements.

Electronic and computing hardware includes central processing units (CPU), graphics processing units (GPU), communications equipment, navigational sensors, and on-board measurement devices such as radiation monitors. A unit's power consumption increases with the number of active on-board electronic devices, necessitating a balance between inspection capability and operational power requirements.

Units will require an on-board power supply to operate both its motion hardware and electronic and computing devices. Power requirements depend on the unit's weight, electronic/computing power consumption, and operational parameters (e.g., operational time and travel distance between recharges). Batteries are preferred to combustion engines in the underground operational environment as batteries do not emit fumes or particulate exhaust. For a point of reference, deep-cycle batteries have been used on autonomous robots in the DARPA Subterranean Challenge and provided a few hours of operational time [46] with sensor payloads of around 50kg [47].

5.1.2 Communication Challenges

For remote robot operation, the IAEA inspector will be situated at a base station, which could be positioned near the repository (e.g., in the above-ground portion of the facility) or in a remote location (e.g., in Vienna). A deep geologic repository is an environment which presents challenges to communication between the base station and the robot system. These potential challenges are a result of a combination of the distance between the unit and the base station, and the amount of geological and man-made material interposed between the underground repository and above ground facilities. It is assumed that existing communication infrastructure will be limited and there will be areas without readily available communication systems. In these cases, the autonomous inspection system can create a self-deployed communication network as it traverses the repository [49, 50]. There have been practical applications of robot systems dropping nodes along the mission route to continually establish communication with the base station while exploring unknown environments [46]. In underground repositories, these nodes would need to be dropped in locations which do not interfere with normal repository operations and allow retrieval by the unit at the end of the inspection mission.

5.1.3 Size and Footprint Considerations

The size and footprint of autonomous units must be considered when discussing the feasibility of robotic augmentation and automation of IAEA inspection processes. Autonomous system design must consider the trade-offs between the size and weight of a unit and its inspection capabilities. A larger system can accommodate more inspection hardware, however transportation between and within facilities becomes more challenging as the size and weight of a unit increase. A robot the size of an automobile would likely not have the fine maneuverability to be effective in the constrained environment of underground repositories. A comprehensive evaluation is recommended optimize the number and type of inspection sensors while meeting inspection capability requirements.

Optical sensors like LiDAR, RGBD, and thermal cameras are relatively small and lightweight, which would allow multiple sensors to be coupled together in a smaller inspection unit. The robots competing in the DARPA Subterranean Competition [46, 47] are examples of units that successfully incorporated multiple devices into rovers with minimal footprints. The width of the emplacement tunnels is reported to be around 4.2m with a similar dimension for height [51], which provides a first-order constraint for design of the robot system dimensions. Deploying small, agile inspection units will allow for high maneuverability through the inspection environment while being inconspicuous to repository workers and preventing disruption to facility operations.

5.2 Inspection Implementation Considerations

According to the IAEA, the primary safeguards objective for geologic repositories is the detection of diversion. DIV will be used to confirm repository design, and to detect potential undeclared activities [52, 53]. This section discusses how a robotic system capable of performing surveillance activities while traversing the repository may support IAEA objectives and augment the DIV process, serving as the primary surveillance mechanism for DIV during an IAEA inspection.

At the highest level, any selected robotic system must be able to meet primary IAEA safeguards measures for a geologic repository. This applies to any level of autonomy desired in the final system. Considering additional challenges, one important consideration for a robotic system is the status of currently available technologies applicable to the task or application. Other important considerations are the time and cost spent in development and testing, which are driven by the expected complexity and novelty of the required algorithms. For example, for software solutions to support fully autonomous DIV mapping, algorithms like SLAM are well-studied, numerous libraries/packages are readily available, and many applications are being researched and developed. However, defect detection for plug surfaces is a novel application and a likely approach would involve deep learning tools like convolutional neural networks (CNNs), which have provided the best results in object detection and feature recognition. Since no direct applications of deep learning currently involve defect recognition for repository tunnel plugs, the networks need to be trained before inspectors can have practical confidence in a network's capability. Finally, nuclear-specific applications involving sensor fusion of different sensing abilities (e.g., temperature, radiation, etc.) may require more research, training, and software development before implementation in autonomous applications. As this would require a cross-disciplinary effort involving nuclear domain knowledge, for now, it is likely that these methods are best suited for shared autonomy mode of operation by trained IAEA inspectors.

5.2.1 Technology Implementation – DIV

DIV is a process that verifies design information provided by the state. In the context of repositories, DIV may also support the detection of undeclared activities. According to Fritzell [52], the DIV for a geologic repository must provide the assurance that:

1. Design information of repository with access routes and other features is verified.
2. Backfill of emplacement tunnels is completed as declared with no voids or other means (e.g., softer fill material).
3. Sealing of back-filled areas are completed as declared.
4. Integrity of repository sealed areas has been maintained through construction phase.
5. Access routes to back-filled areas are filled during the final stages of operational life of the repository.
6. Decommissioning is completed as declared with removal of all surface equipment and facilities.
7. There are no undeclared excavations or boreholes around the repository within a given distance and that none are active during operation or after sealing

There are no undeclared excavations or boreholes around the repository within a given distance and that none are active during operation or after sealingThere are no undeclared excavations or boreholes around the repository within a given distance and that none are active during operation or after sealingThe novel, restrictive, and expansive environment of the underground repositories may present significant challenges to traditional DIV approaches. For instance, the IAEA currently uses 3-Dimensionsal Laser Rangefinders (3DLR) to conduct DIV in surface facilities because of the technology's high resolution and comparison capability [54]. Inspectors rely on 3DLRs on to identify anomalies and potential areas of interest; however, as inspector-carried equipment, 3DLRs are heavy, unwieldy, and would be cumbersome for inspector-use in assessing large geological repositories. Robotic units equipped with instruments like the 3DLR could be utilized to minimize inspector burden during initial and routine DIV inspections. Due to the required training and operational difficulty of 3DLR, the technology is potentially better suited to initial inspections during the pre-operation phase of a repository to establish a baseline and highlight areas of interest for future inspection activities, rather than during the operational phase. However, as 3D range finding technologies evolve and advance, this could change and could find broader application and use.

Robotic inspection systems have already been considered for DIV processes [54] and could serve as the primary means for safeguards inspections in areas that are hazardous or inaccessible. Regular DIV inspections during the operational phase can utilize combinations of technology, a few case examples of which are listed below, to provide assurances of repository design and function. These technologies can address the DIV objectives outlined above and ensure that design deviations and modifications are verified through comparison of observations to baseline information.

LiDAR + Full Autonomy: Addressing DIV requirements (1, 3, 4, 5): Large scale mapping is critical to satisfying DIV requirements. Time-series maps can be generated during each autonomous inspection and compared to historical data. LiDAR technology can be combined with odometry to create high fidelity maps suitable for DIV, on the order of +/-2cm within the actual position [54]. LiDAR has been used previously in applications and environments similar to underground nuclear repository inspections [46, 47, 48, 54, 55] and has precedence and synergies within fully autonomous robotic applications [56, 57].

Optical Imaging + Shared Autonomy: Addressing DIV requirements (2, 3, 4, 5, 6): Optical sensors (e.g., cameras) can provide real-time feedback to operators and allow for visual detection of anomalies and aberrations that require additional scrutiny. Object recognition and flaw detection are topics of machine vision research which receive attention from academia and industry alike. Automatic identification of defects (e.g., voids, cracks) has been used in autonomous applications in other domains [58, 59, 60, 61], however the development of customized solutions specific to IAEA inspections would be required to make this a shared autonomous routine. For example, in addressing DIV assurance requirement 2, it might be challenging to identify differences in strength or composition of materials and validate proper material characteristics from optical recognition or imaging alone. Additional capabilities using tactile sensors, or hyperspectral imaging may be needed. There are also opportunities for development where inspection areas are larger than standard fields of view (FOV), requiring imaging capabilities that allow for multiple viewing angles or minute positioning of the robotic inspection system.

In initial implementation, control of the unit could transition to the inspector to facilitate dexterous robot movement during specific inspection activities. Later implementations can transition to a fully automated routine using active perception [62, 63] based on information maximization.

LiDAR + Optical Imaging + Full Autonomy/Shared Autonomy: Addressing DIV requirements (1, 6): Accounting for declared equipment throughout the facility [52, 54] is another important aspect of DIV. Robotic inspection systems can enhance this process by visually identifying equipment through optical imaging-enabled object detection, determining object dimensions, and tagging object location data on facility maps. It is possible for undeclared equipment to be used for diversionary activities [52], and automating the identification and accounting of equipment could be used to help inspectors verify that that the allotted occupied area falls within guidelines. An example of object detection using the You Only Look Once (YOLO) algorithm [66] is shown in Figure 10.

These activities can be performed with full autonomy, where the unit identifies, categorizes, and flags suspect equipment, or with shared autonomy where control reverts to inspectors if items or areas of interest are discovered [64, 65]. The software would require customized development to detect, identify, and track accountable equipment.

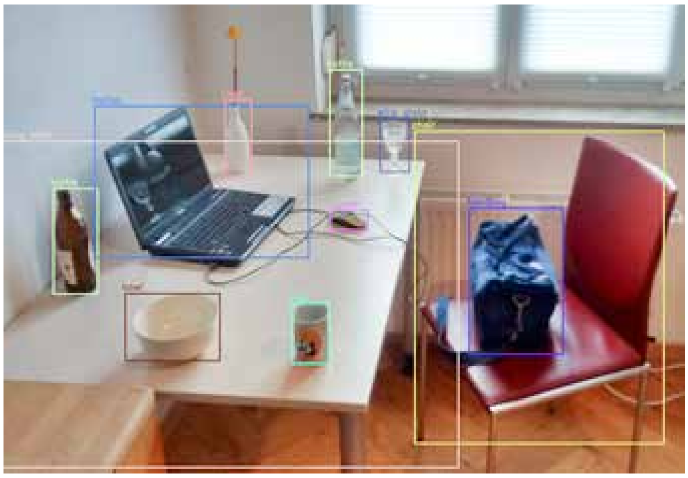

Figure 10: Object detection using the YOLO algorithm [66]

5.2.2 Technology Implementation – C/S of Canisters

This section explores other sensor implementations which are directly applicable to C/S methods. The following list of C/S system requirements are derived from Fritzell [52] and Mongiello et al. [67]:

1. Ensure CoK from above ground activities.
2. Systems are designed for independent operation and remote monitoring.
3. Redundancy within the C/S system is employed.
4. Coverage of all credible diversion paths.
5. Ability to report health status to safeguards authorities.
6. Devices should be tamper-resistant and be capable of indicating tampering has occurred.
7. Devices should have low “false alarm” frequencies.

The focus of the research presented in this paper is on below ground CoK options, therefore consideration of C/S system requirement 1 above is out of scope. CoK of above ground activities can and should utilize existing IAEA C/S measures. Regarding C/S system requirement 6, it is likely that aspects of existing IAEA tamper indicating devices, enclosures, and data security methods can be employed and would need to be implemented for any technical solution described below. A few example cases of C/S technologies in autonomous settings are discussed below.

- **Ground Penetrating Radar + Shared Autonomy:** Addressing C/S requirements (2, 3, 5): Autonomous inspection with ground penetrating radar (GPR) has been accomplished by NASA using their portable CRUX GPR technology [33]. The technology was capable of scanning depths up to 5m and resolutions within 15cm [67] in lunar environments. NASA has also developed a GPR for use with the Martian environment which was capable of depths up to 50m. These portable technologies can be used by the inspection robot system in conjunction with thermal sensors to verify location and presences of emplaced canisters for a dual C/S system.

- **Thermal Imaging + Full Autonomy Addressing C/S requirements (2, 3, 4, 5):** A thermal camera mounted on a mobile unit can capture thermal information as the unit traverses a facility and is able to map out areas inaccessible by the static C/S surveillance approaches [68]. Heat maps of the facility can be matched against historical data with thresholds that are pre-determined to calculate potential diversionary activities. This passive sensing technique can be fully autonomous and set to either collect continuous thermal data during the inspection operation or perform readings at a determined frequency to reduce power draw.
- **Thermal Imaging + Shared Autonomy: Addressing C/S requirements (2, 3, 5):** In addition to fully autonomous thermal sensing, the thermal camera can also be used at the inspector's discretion to examine areas of interest. Specifically, it could potentially be used to match thermal profiles of emplaced canisters underneath the Bentonite clay cap at the end of the emplacement tunnel. During a shared autonomy inspection, the operator could take control of the unit to inspect these emplaced canisters prior to backfill to provide additional verification that the canister is present, thereby maintaining CoK. This verification process would require extensive modelling and testing to be approved as a sound inspection method. In the future, fully autonomous inspection routines can be conducted in a similar vein to the second suggestion in the DIV implementation scenarios, optical imaging using shared autonomy.
- **Radiation Monitoring + Full Autonomy: Addressing C/S requirements (2, 3, 4, 5):** Post emplacement, small low-power gamma and neutron counters can be used to detect off-normal repository conditions, given that the background levels of radiation will be very low due to the presence of the buffer material. Comparing the expected signal with the measured signal could then be used for real-time safeguards verification.

6. Conclusion

Implementing automated solutions for underground nuclear repository inspection will be a new venture for the IAEA but carries the potential to greatly enhance the efficacy and efficiency of inspections and allow inspectors' time and expertise to be directed where needed most. Many different factors must be considered before integration of autonomous solutions into inspection processes. This paper presents a variety of ways in which autonomous units can augment IAEA inspection of underground geologic repositories during the pre-operation and operation phases under varying levels of autonomy and inspector interaction. Sensor technologies for autonomous monitoring are described and hardware systems outlined which can maintain CoK of nuclear waste, adhering to the IAEA safeguards. The permanence of these nuclear repositories allows time for the development of technologies and approaches for augmented inspections. Technology applications that are not yet fully developed can mature by the time these geological repositories are fully functional.

The technology recommendations and implementation scenarios of robotic inspection of underground nuclear repositories in Section 5.2 of this paper provide multiple avenues for follow-on work. There are still many questions to be answered and testing to be conducted. For example, the DIV map constructed via LiDAR and full robot autonomy using SLAM can suffer from error propagation due largely to odometry deviations caused by encoder slippage and other environmental variables. The extent of the acceptable deviations must be tested to gain full confidence as a DIV safeguards approach.

Equipment and data integrity are key requirements for IAEA equipment. Integrity of the data collected by the robotic system and the communication between the rover and the base station must be validated and warrants further examination. The physical unit requires tamper resistance and must be capable of tamper indication. Data streams and samples gathered during inspection must be authenticable. Encryption protocols for data and communication are not extensively considered in this paper and should be explored. Furthermore, research into spoofing of various features that are utilized as inspection criteria and thresholds is necessary. These concerns should be explored early in development to ensure adherence to system requirements and to prevent late-stage changes.

Lastly, additional domain knowledge can be leveraged to maximize the potential of on-board sensors. The efficacy of C/S surveillance via thermal profiles of the canisters under the bentonite cap can be explored using modelling software. Radiological signatures in the environment can be catalogued and tested to identify capable environment sampling sensors which can be mounted on mobile units. This paper can serve as a starting point to the exploration of robotics for underground nuclear repository inspection.

7. References

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