PNNL-SA-153626

Autonomous Inspection of Nuclear Repositories: Current State of the Art and Future Directions

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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. However, the verification challenge remains unsolved, and there persists an outstanding need for tools and approaches that will help the IAEA verify that no nuclear material is diverted from a repository environment. The challenge is also not static. 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. This paper highlights these challenges and outlines how they might be addressed by using remote or autonomous vehicles. Specifically, we discuss 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. We explore the feasibility of using rovers for these verification tasks, 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.

1 Introduction

IAEA inspection resources will become increasingly taxed as more nuclear waste repositories become operational. This paper explores possible robotic technologies to aid and augment IAEA inspection of nuclear geological repositories. Specifically, the recommended technologies are able to help maintain continuity of knowledge (CoK) of nuclear materials during the repository's operation phase. Due to its magnitude, a nuclear repository will transition through several phases: pre-operation, operation phase, and post-operation. The pre-operation phase involves geological assessment of a nuclear waste repository site. The operation phase, the focus of this paper's technology recommendations, is the most complex and involves the construction, processing, emplacement, and backfill of nuclear wastes. The post-operation phase addresses closure of the facility and the long term storage and handling of nuclear waste.

The variability of possible geological waste repository designs and the uncertainty of long term technology development drives a focus on technologies to aid the inspection during the operation phase. Furthermore, each country may have their own variant of a nuclear geological waste repository and designs in various stages of development. For instance, the KBS-3 repository is currently being developed and used by Sweden and Finland [1]. The KBS-3 method developed by SKB provides a model template for the technological recommendations and the applicability of this approach is not limited to the KBS-3 repository design.

During the operation phase, the nuclear waste repository consists of a surface facility (above-ground) and a sub-surface facility (below-ground). The surface facility can serve a variety of functions including simply acting as an entrance to the sub-surface facility or housing a waste encapsulation and cooling plant. Due to the accessibility by

IAEA inspectors to the above ground facilities, this paper will not focus on technologies that can help augment and automate above-ground inspection processes. However, the recommended technologies may certainly still apply to above-ground inspection processes. In contrast, sub-surface facilities have many limitations that prevent easy IAEA inspection. For example, certain tunneling activities will be ongoing concurrent with nuclear waste emplacement and possible backfilling.

2 IAEA Safeguard Objectives

IAEA safeguard measures and approaches for the front end and the back end of the nuclear fuel cycle have matured over the last several decades. However, verification methods for final disposition of spent fuel in underground repositories are just now being formalized as the first underground repository is nearing completion. The IAEA considers the spent fuel disposed in the geological repository to be inherently retrievable and subject to safeguards for as long as the safeguards agreement remains in force. To help prevent and detect such diversion, several safeguard criteria for the final disposal of nuclear waste in geological repositories have been identified, including: [2, 3].

1. Repository design information verification (DIV) during all operational phases
   (a) Compare the declared repository design information to the actual repository facility design
   (b) Detect undeclared exhuming activities inside or surrounding the repository
2. Verify nuclear material content upon receipt of canisters and monitor flow of material
   (a) Verify receipt, continued presence, and declared (and absence of undeclared) transfers of waste canisters
   (b) Detect replacement or removal of material at the gross defect and partial or bias defect level
3. Maintain Continuity of Knowledge (CoK) of nuclear material
   (a) Detect tampering of any container with nuclear material, including shipping casks or waste canisters
   (b) Detect the removal of material from any container, cask, or canister.

A typical deep geological repository will have many tunnels and drifts well below the ground. Once the canister emplacement operation is complete inside a deposition tunnel, that deposition tunnel will likely be backfilled and closed. Therefore, at any instant in time a repository may have a backfilled tunnel, a tunnel in which an emplacement operation is underway, and a empty tunnel. This variability and the inaccessibility of the repository system will therefore pose challenges for implementation of DIV, containment and surveillance (C/S), and material accountancy. This paper suggests autonomous or semi-autonomous methods and approaches to aid in achieving the IAEA repository safeguards criteria outlined above. Specifically, we consider the case of the KBS-3 sub-surface canister system, however the technology could apply much more broadly to other repository systems. The above-ground operational aspects are not addressed here due to the ease of accessibility by the IAEA inspectors. Furthermore, the focus is on operations conducted sub-surface at the repository and assumes that all the relevant data from above-ground operations is passed for consistent CoK of the material.

3 Operation Phase

A typical KBS-3 repository system during operation phase consists of underground openings, nuclear waste canisters, buffers, backfill, and engineered barriers [1]. According to the KBS-3 production report, construction of additional drifts in the underground sections can occur concurrently with the operation phase of the nuclear waste facility [1]. A brief summary of the construction process is provided here to highlight the applicability of the suggested automation technology. More detailed information is contained in KBS-3 reports [4, 5].

3.1 Sub-surface Construction

As per the design of the KBS-3 repository, the main tunnels are excavated, from which the deposition tunnel will branch. These deposition tunnels are drilled for the deposition holes where the buffer and canister will be deposited. It seems pertinent from the autonomous monitoring perspective that the necessary support infrastructure, such as electrical power is available, to ensure the portability of the rover. Furthermore, the terrain that results after the rock construction work should support the rover to move freely.

3.2 Nuclear waste canister

One representative nuclear waste canister design, the KBS-3, involves a corrosion-resistant copper shell that encapsulates the spent nuclear fuel assemblies. The copper shell is designed to properly attenuate the radiation dose rate, to withstand mechanical and corrosion load, and to accommodate multiple fuel assemblies. However, safety considerations related to the long term storage of the waste canister inside the repository limits the maximum decay power and radioactivity at the canister's surface and, subsequently, the number of fuel assemblies that can be included inside a canister. The burn-up data and age of the spent fuel assembly are required to determine the radioactivity and the decay heat of the fuel assembly. The KBS-3 canister has specific guidelines for the acceptable decay power and radioactivity at the canister surface, such as:

1. Maximum permissible decay power: The KBS-3 safety guidelines explicitly state that the total decay power in each canister should not exceed 1,700W. 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 rocks.

2. Radiation dose rate: Similarly, the radiation dose rate at the surface of the canister needs to be less than 1Gy/h. High radiation levels at the canister may lead to the formation of nitric acid and other corrosive species at the canister surface [6].

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

3.3 Buffer installation

When the canister is ready to be emplaced, a buffer of bentonite clay is installed around all its sides. First, the buffer bottom block and ring-shaped blocks are installed. After the deposition of the canister, a buffer block is placed above the canister and caps the deposition hole. The buffer of bentonite clay serves gives stability to the canister and provides protection from underground water to reach the canister surface. This buffer block may serve as a temporary cap if the repository is eventually backfilled.

3.4 Backfill installation

In the KBS-3 repository designs, backfilling occurs after the buffer installation are finished. The backfill procedure begins with the removal of the protective buffer block capping the waste canister and includes the installation of buffer pellets. This step represents the last opportunity for direct inspection techniques such as visual inspection. Afterwards, various backfill installation steps are conducted. Backfilling ends with the installation of the plug. The plug serves as a barrier between the backfill over the deposition holes and the main tunnels. These plugs will be exposed until the backfill process for the tunnel section and as such, the plugs will serve as a focus of inspection to maintain CoK.

4 Autonomous Verification of Nuclear Repositories

This section addresses different robotic technologies which can be employed by IAEA inspectors to maintain continuity of knowledge of nuclear waste in geological repositories. Robotics has been utilized in environments that are similar to underground nuclear waste repositories with goals such as inspection, search and rescue, and exploration [7]. Furthermore, there is active development and government funded projects in progressing the capabilities of autonomous robotics [8]. The technological recommendations are focused on the sub-surface aspects of the operation phase. Each technology recommendation will include general information for practical implementation and current research direction. The autonomous approach section is divided into two subsections. The first section lists the different technologies which can be employed on the robot rover in order to enable IAEA safeguards criteria. These technologies are suggested to be implemented regardless of the level of automation. The second section describes the different levels of automation of inspection implementation. This second section describes the advantages, disadvantages, and considerations for the state-of-the-art automation implementations.

4.1 Robot Sensing Technologies

The verification technologies recommended for implementation on rovers 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 the CoK since the majority of the sub-surface portion of the operation phase does not involve direct visual line-of-sight with the nuclear waste canisters. Additionally, specific implementation details which are dependent on different geological waste repository designs are not discussed in this paper.

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. Specifically, LiDAR has been applied in underground mine environments similar to the proposed nuclear geological waste repositories [9]. Furthermore, airborne LiDAR technology has been used for seismic deformation morphology studies to ensure the geological properties are suitable for nuclear waste storage [10]. Recently, the Joint Research Centre has employed the use of backpack mounted LiDAR for IAEA usage in nuclear facility design information verifications [11]. The very same technology can be mounted on a mobile robot for Design Information Verification (DIV) of the repository during construction and operation stage. LiDAR technology, combined with odometry information, can create detailed digital maps which can be compared to reference facility designs during each routine inspection, addressing the IAEA DIV safeguards criteria.

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 some off-the-shelf software to fuse the data together from different viewpoints. For robotic integration, there may be more specific work necessary to integrate the LiDAR information with odometry information. SLAM algorithms are commonly used in robotic applications to combine the data streams to provide real time maps and floor plans [12].

4.1.2 Feature Imaging

Alongside long-range perception capabilities like LiDAR, short range feature identifications can also support inspection routines. Camera sensors can be an option for short range analysis of defects or disturbances to different components of the geological repositories. These sensors can have a shorter sensing range compared to the LiDAR scanning systems, but have increased resolution and optical distinguishing capabilities like RGB. For example, a camera can be used to visually inspect the surface of a plug at the end of a deposition tunnel and compare with historical data to ensure little to no plug deviations or disturbances. Feature-based identification methods are available and image recognition of defects and surface cavities can be conducted. Furthermore, cameras can be used to supplement or augment seal integrity inspections in surface or sub-surface facilities. These potential applications address all three of the containment and surveillance IAEA safeguard requirements through indirect means.

Similar to LiDAR, imaging technology is readily available and receives support from a variety of industries. A few examples of camera sensor manufacturers are Intel, Sick, and Keyence. The majority of the novel implementation for this application would be in software development. While image displaying software can be configured off the shelf with little to no effort, machine vision and recognition software are likely to be required for more intensive inspection tasks. These tasks can include plug inspection, canister seal inspection, and backfill surface disturbance validation. Algorithms like SIFT, SURF, and ORB have been used readily in applications which require image feature comparisons [13, 14]. These techniques can be used to compare reference images taken at the time of construction completion. In the plug imaging example, these algorithms can be used during each inspection to compare against the images taken at the time of plug installation. Research can be conducted to establish disturbance and deviation thresholds of image matching scores for IAEA safeguard baselines. According to the KBS-3 report on plug designs, the plugs are mostly made out of a concrete material [15]. Image vision analysis for concrete damage detection is an active research area [16] and the IAEA itself has considered non-destructive testing techniques for concrete inspection [17]. Camera technology can augment IAEA inspectors, providing additional feature identification capabilities and the necessary visual feedback.

4.1.3 RFID On Metal Tagging

Radio-frequency identification (RFID) tags are commonly used to uniquely identify objects. Tags are attached to an object and are later identified with the help of a reader or interrogator. RFID systems have a integrated circuit and a transponder which communicate to a RFID interrogator through radiowaves.

However, traditional RFID tags may not be applicable in a subsurface repository, since canisters like the KBS-3 are made of copper and the buffer layer may prove to be a barrier for the communication between transponder and the interrogator. Therefore, a magnetic alternative to RFID, RFID-on-metal, which uses a packet-based wireless technology may be a good alternative. For example, RuBee(IEEE 1902.1) [18] is a RFID-on-metal tagging system which is accurate even when attached to a metal surface. The wireless signal also has the ability to travel through solid materials [19]. Additionally, it comes with a long battery life of more than 10-25 years which is compatible with the KBS-3 canister use case in nuclear repositories. Integration of a reader suitable for the detection of an RFID tag can be accomplished on a rover, [20] making this a potential approach to verify the continued presence or movement of material, particularly before any backfill stage is initiated.

4.1.4 Measurement and Detection of Radioactivity

The radioactive nature of the spent nuclear material means that it emits a characteristic spectrum of gamma and neutron radiation. Non-destructive assay technologies to measure the radiation signature are widely available from many commercial vendors in the form of probes, in-situ object counting system, coincident counters, and area monitors [21]. Additionally, computational tools such as SCALE [22] and ORIGEN [23] are helpful in the prediction of the theoretical decay power of spent fuel, isotopic inventory and radiation source terms. Using the information passed on from the above ground operations, the characteristic radiation of the nuclear waste canister can be estimated theoretically as a function of time.

Comparing the computed spent fuel characteristics obtained from SCALE/ORIGEN with the direct measurement of spent fuel characteristics using the traditional non-destructive assay methods can serve as an indicator of appropriate material content. Further, this comparison when carried out before the canister emplacement could also assist in maintaining the CoK of the material. Computational models can also be used to assess the impact of the attenuation of the copper canister on the radiation signature. Measuring this signature after the emplacement, provided the impact of the buffer is also characterized, may be a viable material accountancy approach. Assuming 662 keV gamma rays and a polyvinyl polymer coated bentonite clay [24] density of 2.8 g/cc, we roughly estimate that 70 cm of buffer will cause gammas escaping the canister to be attenuated by at least a factor of 10^8. More sophisticated calculations of the radiation signature after the attenuation due to copper canister and bentonite clay will be necessary using modern radiation transport codes such as MCNP [25].

4.1.5 Temperature Profile Measurement

Similar to the characteristic radiation signature, the decay power (heat) of a fuel assembly is dependent on its burn-up, age, and mass of radioactive material. Decay heat can also be estimated using SCALE/ORIGEN or other similar software packages. With knowledge of the decay heat source term, the temperature in the buffer region of the repository where the canister is emplaced can be computed with the help of modeling and simulation software such as ANSYS [26]. The computed temperature at the buffer's surface can be compared with the actual temperature measured as a qualitative material accountancy technique.

The surface temperature measurement can be performed using an infrared thermographic camera. A thermographic camera works on the principle of detection of infrared radiation emitted by an object as long as 14,000 nm [27]. A thermographic camera is also amenable to rover installation. This method, however, is applicable only before backfill is initiated.

4.1.6 Ground Penetrating Radar Systems

Ground-penetrating radar (GPR) is a subsurface imaging method that involves the use of radar pulses in the microwave band of the radio spectrum. The frequency of the radar pulse could be optimized with respect to the reflective characteristic of the buffer material. For creation of subsurface image, a radar pulse is transmitted through the surface material and the strength and time of reflected signals is recorded. Reflections are produced based on the electrical conduction properties and dielectric permittivity from the material from which reflections occur. Metals act as a complete reflector and thus do not allow any amount of signal to pass through. If an area is to be scanned, then a series of pulses will be sent throughout the surface [28].

The difference in the electrical conduction properties and dielectric permittivity between the bentonite clay and copper canister will allow GPR to be used to verify the continued presence of the waste canister emplaced under the buffer surface before backfill. A GPR system commonly consists of a control unit and antenna, in which the function of the control unit is to generate the radar pulse while the antenna sends that pulse into the ground. GPR systems are available commercially from 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 the rover [29]. For pre-backfill conditions, GPR technologies are an attractive option for containment and surveillance activities at a repository.

4.1.7 Ultrasonic Evaluation

The copper canister consists of a bottom plate, a tube and a lid. After the fuel assembly is encapsulated inside the copper canister it will be sealed using the friction stir welding process. However, this process to join copper surfaces leaves an air gap between the surfaces. This gap represents a discontinuity pattern related to the change in the gap height that is unique to the canister. This specific discontinuity pattern can be successfully detected by an ultrasonic transducer [30].

This technique is very useful for verification upon the receipt of the copper canister at the repository before emplacement. Installation of a ultrasonic transducer on a rover [31] and use of low frequencies will aid the unique identification of the canister emplaced under the buffer. Ultrasound can be used to uniquely identify the canister on the basis of the discontinuity pattern of the canister's weld surface and will also establish its integrity and aid in detecting tampering or diversion attempts in pre-backfill repository environments.

4.2 Levels of Automation

A robotic rover can augment direct IAEA inspections of the geological waste repositories by providing the inspectors with an extension of sensing capabilities. Beyond the validation technologies which characterize the robotic rover's sensing capabilities, a large consideration must be made to the automation capabilities. Specifically, the method by which the robot rover maneuvers around the environment requires additional research and adaption to different repositories to take full advantage of robotic automation benefits. This section describes three different methods of operation, each with their own advantages and disadvantages. Each method may be the proper solution for IAEA inspection depending on many external factors such as timeline, repository environment, budget, and technological availability. Further research into each method is encouraged to fully evaluate feasibility of each method.

4.2.1 Fully Autonomous

Fully autonomous solutions 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 each system 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 for status of each robotic system. This can provide strong efficiency gains from current inspection techniques.

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 unknown environment navigation, task allocation and scheduling, robotic localization, path planning, and multi-robot coordination.

Some examples where these fully autonomous aspects may be applied to IAEA inspection methods to underground waste repositories are given, but further detailed research is recommended for each specific nuclear repository. Exploration of unknown environments require algorithmic challenges that processes the perception information (e.g., LiDAR scans, camera images) and returns a direction of desired travel. Even with the given ground truth information of repository design layouts, different deviations and potentially undocumented drifts may be present which require these approaches. A popular method, frontier-based exploration algorithms, has proven successful and has been commonly applied in the robotics community [32, 33, 34, 35]. In another example, task allocation and scheduling can be applied to organize sub-objectives alongside the main objective of nuclear inspection. The deployed system would be capable of navigation along the environment, but may encounter a variety of sub-tasks such as plug inspection scheduling or additional deposition hole verification [36]. The algorithm would have to balance parameters such as remaining mission duration time and power supply with the benefits of maximizing plug inspection versus deposition hole verification. These kinds of desired mission outcomes can be programmed beforehand by the operators. Finally, the last example considers the case where multiple robots may be deployed at once into the underground repository. This can enhance the efficiency of the inspection trip by increasing the amount of ground covered. When these robots are deployed, they would require scheduling and coordination amongst each other to maximize parameters like ground covered with most amount of inspection goals accomplished [37, 38]. Furthermore, this kind of multi-robot coordination would need to consider the potential drop in communication between each robot and plan accordingly in a decentralized manner [39, 40].

4.2.2 Semi-Autonomous

A semi-autonomous solution can incorporate desirable elements from fully autonomous or manual approaches at a more reasonable complexity. This approach can be flexible and adapt to certain situations at the cost of certain capability trade-offs. Furthermore, a semi-autonomous solution can be implemented as a stop-gap between the manual and fully autonomous approach, with incremental features developed and implemented at separate times. An example of a semi-autonomous solution can involve way-points and certain task commands issued by the inspector. The robot may then begin to execute on these commands in an autonomous fashion, reverting to manual operation for more complex, sensitive, or difficult tasks. Additionally, autonomous sub-routines may be installed for the robot to take over if communication with the operator is lost. These routines may simply involve recovery behaviors like backtracking to the last known position within communication range.

Semi-autonomous solutions can vary in the degree of human collaboration that is required [41]. Implementations can evolve with advances in technology and algorithms, with the possibility that early implementations of semi-autonomous solutions require more operator involvement. Later iterations of the implementations can incorporate more autonomous features, reducing the operating load on the inspectors. Ultimately, continuous improvements on the semi-autonomous system can lead to a near or fully autonomous solution.

The semi-autonomous solution can incorporate different levels of autonomy mentioned in the fully autonomous section. In addition to the fully autonomous robotics research, the semi-autonomous robotics research includes fields like human-robotic collaboration and hybrid control schemes. In the case of nuclear waste inspection, an example of human-robot collaboration would be graphical user interface (GUI) designs which helps maximize the productivity of the IAEA inspector without inspection result information overload. The verification technologies returns information in different forms, such as radiation measurement graphs or deposition tunnel backfill quality. The display of these different information to operators can be studied and modified to desired traits like maximizing the operator's interaction with the rovers [42, 41].

Understanding of human-robotic collaboration can also include the creation of an input control system (e.g., joystick, controller, keyboard) which can be easily operated or send information back to the robots. Depending on the complexity of the automation, a more complex input control system with more total inputs available may be required. An example of hybrid control schemes would facilitate interactions with the human during navigation and rover motion. Specifically, if the IAEA inspector observes an area of interest, the operator can designate the task for the robot to execute the inspector's order. Upon closer inspection of the area interest, the inspector may desire manual control in order to have a more detailed search. This alternation between autonomous self-guidance and manually controlled can require a flexible control scheme which is capable of both types of operation [7]. Next, if the semi-autonomous system favors manual operation, there can be autonomous sub-routines built in. These autonomous sub-routines can be executed in the event of loss of communication. If the operator no longer has control and communication with the robot, the robot can execute the autonomous algorithm which enables it to return to a last known position of communication range. Another example with communication loss can occur during inspections of undeclared tunnels or sections. Autonomous inspection routines can be built to be executed if the area of interest is outside of communication range and then return back into communication range.

4.2.3 Manual

Lastly, robotic teleoperation is a fully viable solution which has been used in a variety of applications [43]. In this operation mode, the operator has full and direct control of the robot's motions and planning capabilities. An example of manual operation would involve the operator sending motion commands to the robot from the basestation based on visual feedback obtained by the rover using onboard sensors. This basestation can be on-site at the nuclear waste repository or remote in another location, provided constant communication is maintained.

The teleoperation option is the easiest to implement based on the pedigree of the technology. However, the performance of the system is highly susceptible to communication quality between the operator and the rover. Furthermore, it also requires substantially more operator training. Practical implementation of this technology would require a permanent communication network to be setup along the main and deposition tunnels in the underground facilities, which would expand alongside construction. Another implementation could be a temporary communication network set up by the robot, which drops retrievable communication nodes along the way [44, 45]. While the technology is easy to implement, it has the downsides of requiring the full attention of the operator. This limits the ability to deploy multiple robots, thereby likely reducing efficiency gains that would be had with more autonomous solutions.

5 Conclusion

This paper presents a variety of robotic technology recommendations that can augment IAEA inspection of underground nuclear waste repositories during the operation phase. The sensing technologies section outlined hardware which are able to maintain continuity of knowledge of the nuclear waste, adhering to the IAEA safeguards. The levels of automation section highlights three different modes of robot software implementation and operation by which the robot(s) can execute the inspection objective. The long term purview of these nuclear repositories allows significant flexibility in the design and implementation of robotic inspection technologies. Technology recommendations that are infeasible now can mature by the time these geological repositories are fully functional.

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