WHITE PAPER

How autonomous robot localization enhances health physics and source characterization in moderate and high radiation environments

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This document explores how the continuous collection of radiation monitoring data from an autonomous robotic platform both enhances existing survey profiles, and opens up the opportunity for entirely new kinds of survey operations when radiation sensor data is paired with other types of data collected in parallel.

Autonomous Radiation Survey Advantages

Reduced human dose

The ability to remotely collect survey data for the classification of radioactive areas and sources has always had the obvious effect of minimizing human exposure to ionizing radiation. This is a clear and easily-understood advantage for ALARA purposes, and has been a fixture of operations inside of nuclear facilities since the earliest days of harnessing the atom for power generation. Initially, this came in the form of fixed sensors which relayed dose rate information to operators who could remain outside of areas with high radioactivity.

Mobile robots increased the reach of operators by allowing them to have a mobile presence inside those areas, with the capability of bringing cameras and remote sensors into hazardous environments, as well as basic manipulation tasks. In some cases, these operations are ones which could be accomplished by a human being that would absorb a controlled quantity of ionizing radiation, while in others the radiation dose rate is high enough that human beings could not perform the task due to the dose rate being too high. In both circumstances, the removal of the need for any human dose is at minimum, preferred, and can be outright necessary.

When the environment is particularly challenging to navigate, communications are limited, and reliability is critical to safety, having a platform that can operate with a minimum of operator intervention is key to reducing human dose.

Repeatability & Task Parallelization

Even if radiation protection surveys are not scheduled, they are almost inevitably conducted on the same profile each time, and involve checking the same equipment and locations. Allowing human operators to have a tool that speeds up the task of quantifying and mapping radioactive areas autonomously amplifies their ability to maintain safety on a wide scale.

We'll cover the specifics of which surveys benefit most from mobile autonomy further down in this document, but besides human dose savings, the ability for an autonomous mobile platform to collect highly repeatable data is a key benefit for facilities where radiation protection surveys are common. It eliminates inconsistencies between different human operators, and can make survey data available to show trends over time by increasing the granularity of its collection times.

Continuous Mobile Monitoring

This function in particular is the primary focus of this paper. The concept of mobile autonomy opens up an entirely new capability in radiation surveys that has not traditionally been conducted. While it can replicate the majority of existing survey by taking readings at designated predetermined locations, the ability to record dose rates continuously while in motion, and plot the results in both 2 and 3-dimensional space with centimeter (or greater) accuracy enables the creation of radiation maps that can display information on dose rate and contamination zones on a level that's not before been seen in the nuclear industry.

This localization, when aligned with sensor data collected in real time, turns any device that navigates autonomously through an environment into a system that can collect continuous data from any location at any time, storing it for later analysis or even alerting operators to conditions that require immediate attention that would otherwise require fixed sensors to be placed at intervals that would never be feasible to deploy.

This capability creates visual maps that can be easily interpreted by operators, maintenance personnel, and health physics alike. It also enables the discovery of areas of high radiation that might have not been otherwise discovered, by showing dose rates at all points along a route, rather than exclusively at predetermined points.

It creates a low operator effort method for:

- Supplementing pre-set locations with comprehensive dose rates to highlight unexpected hot spots
- Providing the opportunity to notify plant personnel of emergent circumstances immediately and automatically
- Creating detailed radiation maps for pre and post-work analysis of shielding effectiveness
- Modeling contamination and dose rate information in 3D
- Supplementing human operators with easily-interpreted data when creating radiation work briefings

We're going to discuss some of the methods by which this has been accomplished, and share some examples of where this capability has already shown huge benefits for nuclear operators that are leveraging this technology.

Existing Radiation Survey Profiles

The goal of this document is not to exhaustively cover the concept of radiation surveys themselves. This is a topic which has a great deal of depth and breadth involving a myriad of sensor types, mission profiles, practices, and schedules, and is already extensively documented elsewhere. It is, however, important to discuss which types of surveys are most applicable to this technology, and why.

The type of survey where mobile autonomy brings the most value include those where any combination of the following factors can be true:

1. The sensing device needs to be moved either continuously or positioned at various locations and/or positions during the course of a survey
2. The environment itself is either known to be, or has the potential to be hazardous
3. The execution and accuracy of the survey is fully dependent upon continuous, direct human action

For this reason, we will not be talking about fixed continuous dose rate, air monitoring, or bioassays. These are all effectively handled by fixed sensors.

Health Physics / Radiation Protection Surveys

The most frequently-conducted surveys are those performed by facility "health physics" departments for the purpose of radiation protection. Measurements are taken at various locations within an area, with the primary intention of understanding what the effective human dose will be when working inside the radiologically controlled area or RCA. This most frequently consists of area dose rate measurements at various elevations, and occasionally includes locating and classifying areas where fixed or loose contamination are present. Since these surveys require human entry, these personnel are nearly always exposed to a controlled, but non-zero amount of ionizing radiation as part of their job.

The health physics department will utilize the data collected during these surveys to set up any appropriate signage and identify areas of high and low radiation dose rates. They utilize these maps and indicators to author safety briefings for anyone entering those areas once the survey has been completed.

These processes are conducted before any work is done inside the RCA, as well as on a periodic basis in critical areas. They are highly repetitive, fully manual, and very "analog" in nature (most data is hand-written on paper before input into digital systems of record, if they're entered at all.) They're also exclusively conducted inside facilities which contain radioactive material as part of normal operations.

Source characterization

This is the process by which a source of radiation (either in an RCA or in the field) is located, identified, and classified. IAEA TECDOC-1344 defines it as a system: “based on the potential for radioactive sources to cause deterministic health effects. This potential is comprised partly by the physical properties of the source and partly by the way in which the source is used.”

While a general health physics survey is meant to understand what the health effects are of entering a radiologically-controlled area, the process of source characterization is designed to ensure that the radioisotopes that are causing the radiation are understood both in their composition, and quantity. These surveys can often involve more specialized equipment such as scintillation detectors for identifying specific isotopes by their energy spectrum. It can also involve the use of a variety of sensors to locate source material through positional methods.

The practice of source characterization extends beyond facilities with known nuclear material. It’s also conducted during emergency CBRNE response activities.

Nuclear site regulatory “downposting”

This type of survey is conducted at locations where the radioactivity is high enough that the site itself has been given a specific regulatory status that prevents certain activities from taking place altogether. Most frequently, this is a scenario that occurs during the process of nuclear decommissioning The purpose of these surveys is to validate criteria for a reduction of a site’s overall radioactivity / contamination status to allow for a less restrictive regulatory categorization.

For instance, a facility that has locked high-radiation areas (LHRA) that are no longer in operation, with their radioactive isotopes secured and disposed of, can have their regulatory status reduced by performing a downposting survey to ensure that dose rates are below a threshold at locations within a given proximity to features and equipment.

While a much less frequently-conducted survey than the two mentioned above, it is one that benefits from mobile autonomy the most in terms of human dose reduction and the scope of the effect that the collected results has.

Enabling Mobile Autonomy

General Concepts of Robot Localization for Interior Environments

Even when prevailing systems such as GPS are unavailable or unreliable, there are a number of ways that devices can have their location tracked within the three-dimensional space of an environment. These methods tend to have “local” consistency, but can be aligned with “global” markers in order to turn their coordinate systems into ones which align with human-readable maps and visual position indication systems. Each of these various types of localization systems have advantages and disadvantages, and many can be combined or coordinated together to enhance their accuracy.

Inertial Odometry

Even if a robot has no sensors or systems in place to identify where it is relative to its environment, inertial navigation systems (or INS) can utilize accelerometers and/or gyroscopes to track where the robot is relative to where it first powered on and calibrated itself. Modern inertial navigation systems have become much more compact and portable due to the miniaturization of accelerometers. This system is “global” in that the device will track its position relative to the start of its operation until it is powered off, and therefore does not depend on reference to the “local” environment. As long as the point of origin is known to be aligned with a fixed location, the coordinate output of this system can determine the robot’s location anywhere in the environment.

On its own, inertial navigation is one of the easiest to implement because it requires no external sensors or consistency within the environment whatsoever. For these reasons, submarines have traditionally used INS as their primary means of navigation through the use of large, powerful and highly-accurate gyroscopic systems that can track the location of the vessel in an area where no signaling or nearby features exist. In essence, it can allow a vehicle that’s entirely “blind” to have a functional form of navigation relative to an initial location fix.

The downside of this system is that all INS eventually experience “drift” in their accuracy the further they travel from their point of origin. Sensor noise, bias, vibration, and excessive rotation can all impact this drift factor, and so for robotic systems this drift can significantly impact the machine’s operational distance, particularly in environments where the control system does not have a predetermined path to follow. The good news is that this drift can be offset through the use of other supplemental forms of localization, even those that are intermittent, making inertial navigation still a highly useful component of any system of mobile autonomy.

Visual Navigation

This exceedingly general terminology is often used as “catch-all” for forms of localization that involve cameras or other external sensors that detect features of the environment around the robot for the purpose of understanding the device’s location and orientation.

Visual navigation includes photogrammetry, movement tracking, and comparing known previously captured images to what the robot presently sees. It requires the use of external sensors, and the ability to “see” the environment in order to create and match visual “landmarks.” When there’s a high degree of visual consistency and uniqueness to the environment surrounding the robot, visual navigation can provide a very high degree of “local” accuracy relative to its immediate surroundings.

The “global” accuracy of visual localization is not particularly good, however, because it depends on the consecutive accuracy of each previous visual “bookmark,” and therefore can be subject to more global drift than an INS experiences. Its accuracy can also be impacted by changing lighting conditions, high contrast environments, and occluded areas that cause the sensors collecting the imagery to have difficulty matching to previously known landmarks.

This “global” accuracy can be improved through SLAM-style “loop closures” obtained by traversing through the same areas and intersections multiple times, supplementing with additional forms of localization, and the use of unique global localization markers.

Visual localization markers require no electricity, and can be placed on flat surfaces throughout a facility to drastically improve robotic localization. In order for them to be effective, however, there are requirements on their use:

① They must be unique for the totality of the environment where the robot will need to navigate. Duplicate markers would be akin to your GPS receiver showing the same coordinates for two different locations.

② The markers must not move relative to the robot’s path. They cannot be placed on a temporary structure, or on moving partitions or platforms. Permanent walls that the robot can approach without objects blocking them are the best choice. Floors can be a viable option as well, provided the fiducials are kept clean and in good condition.

③ These markers must be reliably visually identified. This means they should be placed in a location with effective, consistent lighting, or be actively lit in some way, and the robot must have line-of-sight to them when it passes through the location.

④ The placement of placards inside of radiologically-controlled areas may require additional approvals and procedures, so be aware of your organization’s regulatory and procedural requirements in this area.

Visual navigation can be enabled with video-based sensors and cameras, or it can utilize depth information to create point clouds with stereo and laser-based systems. The latter usually provides much better localization accuracy and repeatability, and will frequently extend the “reach” of the robot’s visibility to cover areas of much wider-open space. This is why LiDAR-based systems are most frequently used for SLAM and the creation of “digital twins.”

Radio Frequency Localization

GPS signals are exceptionally weak and cannot penetrate walls, but using radio frequencies for triangulating a device’s location is still a common choice for creating functional indoor localization that doesn’t depend on external sensors or visibility.

These systems can be implemented using ultra-wideband (UWB) radio beacons, bluetooth, RFID, WiFi, and other proprietary radio-based systems. In optimal conditions, these systems can provide < 1 cm location accuracy with very minimal data transfer requirements.

RF-based localization is more often seen in warehouses and logistics use cases rather than industrial ones, since they can be significantly degraded by the presence of heavy mechanical equipment and often do not penetrate walls well. They also require the installation of new permanent equipment which requires power and network access, adding cost, administrative, and security considerations.

Map Anchoring

Regardless of which of the above systems are used to perform the localization process, once the robot itself is localized there needs to be a way to inform the operator what that location ultimately translates into from a human perspective. From a technological perspective, all of these systems ultimately output the device's position as a set of 2 or 3 numbers that designate its coordinates relative to somewhere else.

GPS coordinates, for example, designate latitude, longitude, and elevation in the form of numeric differentials relative to the equator, international date line, and MSL or "mean sea level." This makes it easy to "anchor" a GPS-sourced map onto a globe or other visual representation of the world terrain, such as satellite imagery. Other localized coordinate systems will likewise have some fixed point which serves as the location that all subsequent coordinate outputs are relative to.

"Anchoring" the output of these systems to known real-world locations with a high degree of accuracy can provide not only a way to overlay human-readable maps and contextual information, but also can improve the overall accuracy of the localization process itself. For instance, when visual markers (mentioned above) installed in a facility are aligned with a blueprint, this turns those three numbers into a visual representation of where the robot (or the data point the robot collected) is physically located. This data can then be shown in real time to provide an operator with direct access to the telemetry the robot is collecting inside of a human-denied location, or to plot that data on a visual map for the various surveys described towards the beginning of this document.

For Boston Dynamics' Spot platform, the SDK provides an easy way for customers and partners to benefit from Spot's patented data mapping technology, and anchoring that data onto a customer-provided blueprint. Code examples and tutorials of how to accomplish this are provided on our website here:

`https://dev.bostondynamics.com/python/examples/graph_nav_anchoring_optimization/readme?highlight=anchoring#anchoring-optimization`

Real-World Examples

ISFSI Pad Monitoring - Talen Energy

While operating the Spot robotic platform with a radiation sensor integrated into the robot's localization data, nuclear operators were able to immediately see the benefit of increased data granularity.

The map below was generated during an autonomous mission where Spot provided radiation dose rates at the numbered locations around the spent fuel storage pad of a BWR power plant. The map was aligned with geographic data in order to show a visual representation of where the robot was during its mission.

The numbered locations were predetermined survey points where the robot held still for a few seconds to allow the dose rate estimator to balance, and then recorded the 5-second average as the value. However, you'll note that there are colored lines between all of the survey points which correspond to the legend on the right. This is where the robot records a new dose rate every 2 seconds while it is in motion. These "breadcrumbs" become a trail of dose rates behind Spot as it walks.

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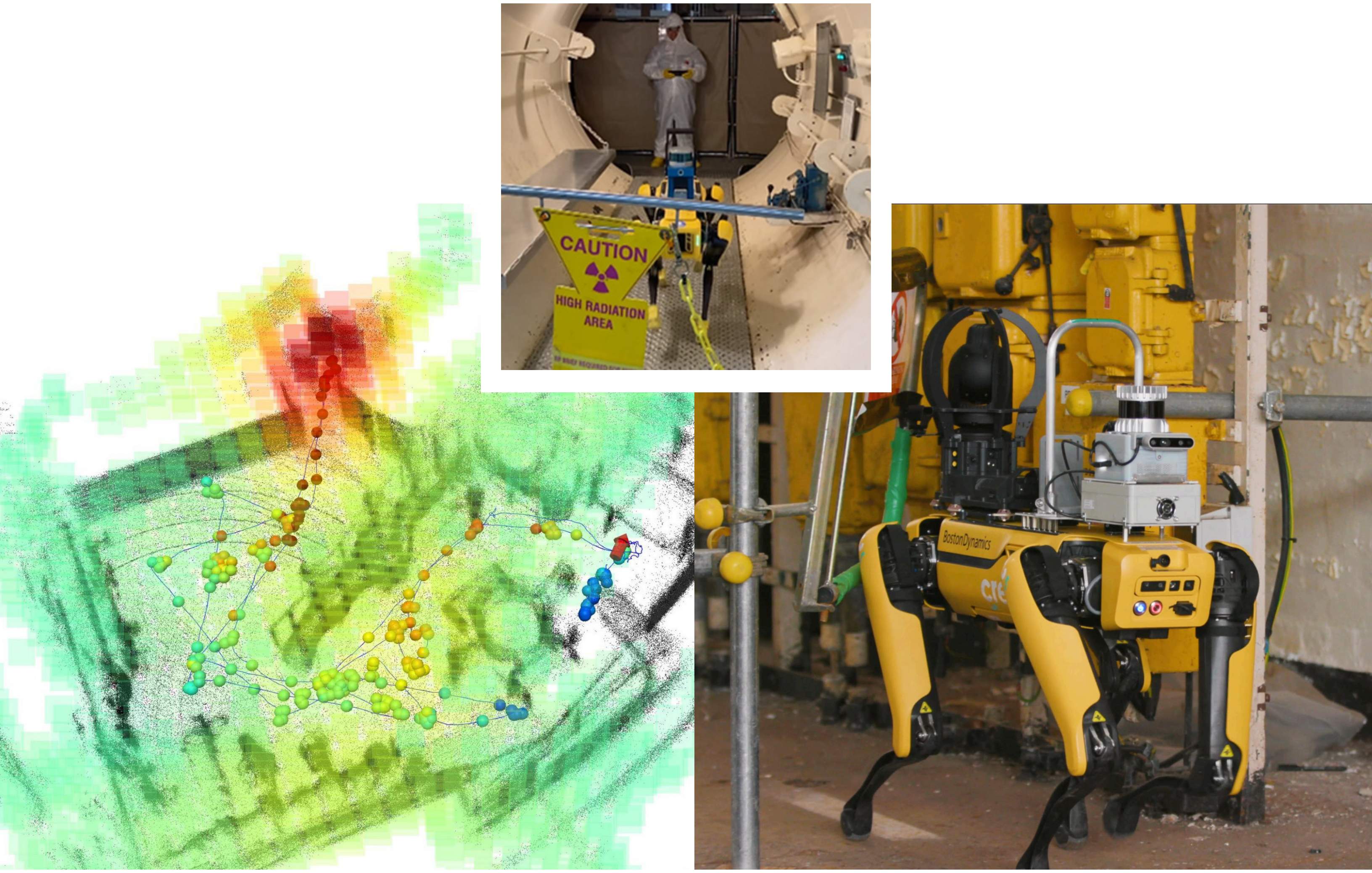
The clear difference between the pre-set survey points and the visual map is the highlighted high dose rate area between survey points 7 and 8. Even though the individual survey points showed dose rates as low as 1.1 mR/hr, the dose rates between them were significantly higher, even approaching 5 mR/hr. The operator could immediately determine at a glance where the most recently placed fuel was located. Additionally, the sensor was configured with a dose rate alarm that could remotely trigger events, so if the robot detected abnormally high radiation during a routine survey, operators would immediately know, even if the alert took place somewhere outside of the designated survey points.

Shielding Efficacy Evaluation - (Dominion Energy)

During a maintenance operation, Dominion Energy wanted to obtain a detailed view of what the relative radiation dose rates were at various locations within a power plant before, and after, the installation of additional shielding.

This process was conducted with a “LAMP” (Localization and Mapping Platform) sensor developed by Gamma Reality which produces a 3D model of the environment, and performs autonomous localization of the relative dose rate information within the area. Spot carried the sensor system through a planned route to perform a baseline survey during plant operation, and then a planned shutdown enabled crews to install additional shielding materials. After the plant was once again operating, Spot re-entered the environment with the LAMP sensor and was able to produce a second map showing the updated areas of high and low radiation to validate the shielding’s efficacy.

The image below shows the result of one of these scans, with the highest radiation recorded at the upper corner. During this process, Spot simultaneously saved a significant amount of human dose which would have otherwise had to be absorbed by a radiation safety worker in order to conduct the survey.



Nuclear Decommissioning

Spot has been deployed at several nuclear sites that are presently in a state of being decommissioned. During these deployments, Spot entered highly dangerous locked high radiation areas (LHRA) to perform manipulation tasks with the Spot Arm for clearing debris and enabling remote human operations, as well as conducting visual surveys and mapping radiation dose rates. The Spot robots deployed in these facilities have absorbed a great deal of total radiation dose and contamination while continuing to operate. Presently, the highest total dose recorded on a Spot robot used in nuclear decommissioning is approximately 13 Sv (1,300 Rem.) As of this printing, no Spot robots have yet experienced system failures due to radiation.

In Japan, Spot was used to inspect the site of the nuclear accident at the Fukushima Daiichi power plant in Units 2 and 3. The fuel handling machine control room in Unit 2 had been untouched since the accident. Spot accessed the outer chamber of the unit, climbed up several stairs, and then opened the door to gain access into the control room, where it took dose rate readings, collected several radiation surface contamination samples, and video of the interior.

In the United Kingdom, Spot has been critical to the process of collecting and removing debris from inside hot cells at the Sellafields nuclear site. Spot has moved enough waste to fill 18 Plutonium Contaminated Material (PCM) drums from 12 hours of work. The robot has also been used to substantiate first floor stairs & gantries, and a Leica laser scanner has been carried out using SPOT to support understanding the structure of the cell to inform Design & Engineering.

Conclusion

The alignment of robotic localization data to scalar data such as radiation dose rates not only enables the autonomous collection of radiation survey data without the need for human exposure, but also the accuracy and granularity of that data. It can fill the need for enhancing ALARA practices, and provide previously difficult or even impossible types of radiation maps.

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