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Deployment of an automated robotic solution for redundant operations and human risk mitigations

Hugo Maurin[2], Sebastian Kohn[1], Oliver Sommer[1], Adele Weber[1], Frank Querfurth[1], Felix Roesel[1], Lucas Soubeyrand [2*]

[1]Framatome, Paul-Gossen-Straße 100, 91052 Erlangen, Germany
[2]Framatome, 2 Rue Professeur Jean Bernard, Lyon 69007, France

*Corresponding author, E-mail: lucas.soubeyrand@framatome.com

Since the arrival of robotic in the industrial field, many solutions have been deployed to increase productivity, lower the risks due to certain operation and avoid long term and repetitive tasks performed by worker.

In the operation of nuclear power plants, numerous tasks continue to be performed manually by on-site personnel. These tasks include measuring radiologic contamination in road sections, potentially contaminated equipment, and hot storage areas. This process requires an operator to place a contamination monitor close to the surface accurately and repeatedly over large areas. Additionally, when contamination levels are too low to be detected by monitors, wipes are used to collect samples from some aforementioned examples.

The AMORAC project focuses on advancing the development to assist human operators in their daily tasks using a mobile base Spot® from Boston Dynamics. This involves integrating autonomous tasks with the automated contamination measurement process into the existing system, with particular emphasis on measurement rules and the resulting documentation. This article presents the deployment of AMORAC on several test campaigns as well as other potential application.

KEYWORDS: Robotics, automation, risk, contamination, AMORAC

Introduction

The global landscape of nuclear energy is marked by the presence of 441 operational nuclear reactors, with constant needs of control. These facilities necessitate a considerable quantity of measurement activities for the safety and status characterization, which involves conducting clearance measurements on a vast array of surfaces. Additionally, objects such as transport containers require regular contamination assessments. Traditionally, these tasks are performed manually by holding a contamination monitor against each surface for a specified duration. A primary objective of this project is to alleviate this manual workload through automation.

The methodology for conducting contamination measurements is contingent upon the geometric configuration of the surface in question. Environmental factors, particularly soil properties, can pose significant challenges for robotic platforms. Another ambition of this initiative is to develop a versatile solution capable of addressing various tasks related safety improvement, such as dynamic measurements without direct contact, extending to radiation surveillance activities or intervention during incidents. This broad an array of complex use cases has driven the decision to employ Spot® from Boston Dynamics, particularly the version equipped with an articulated arm. The initial focus, however, is on automating α, β surface contamination and ɣ dosimetry measurements at close proximity to surface patches.

AMORAC specifically targets to fully automate clearance measurements. To achieve this, additional hardware has been adapted and installed on the robot. Broadly speaking, AMORAC addresses the challenges associated with free-release by fulfilling the need for radiological characterization across diverse surface types and sizes through precise and localized radiological measurement. Furthermore, it synchronizes measurement results with existing documentation, whether in PDF, paper, or digital formats. By automating these processes, AMORAC not only addresses the scarcity of human resources but also enables operators to focus on more complex tasks, rather than engaging in repetitive measurement activities. It stands as an effective tool for preventing musculoskeletal disorders.

Figure 1 : AMORAC measuring a wall for contamination characterization

The forthcoming sections will delve into the deployment of AMORAC in different nuclear installations such as nuclear power plant and hot bases performing different tasks of contamination measurements on a range of surfaces.

Deployment of AMORAC at Blayais, an operational NPP

The test campaign at Blayais, a French NPP, aimed to highlight capacities and limits of AMORAC on different measurement tasks. In the end of 2024, AMORAC has been selected to perform automated clearance measurements in the running plant. Four areas have been chosen: road control to inspect if any leaks of contamination have happened during transportation of contaminated objects, BCT area that is the incoming and outcoming control area and the hot tool storage area, and the machine hall as complex and representative environment of any reactor building.

- Nuclear Power Plant roads must be inspected completely once a year and each week when the plant stops for fuel reloading (roads used for contaminated objects transportation). Thus, two tests of gamma and beta radiation ground control have been conducted on both road directions of the site's main entrance.

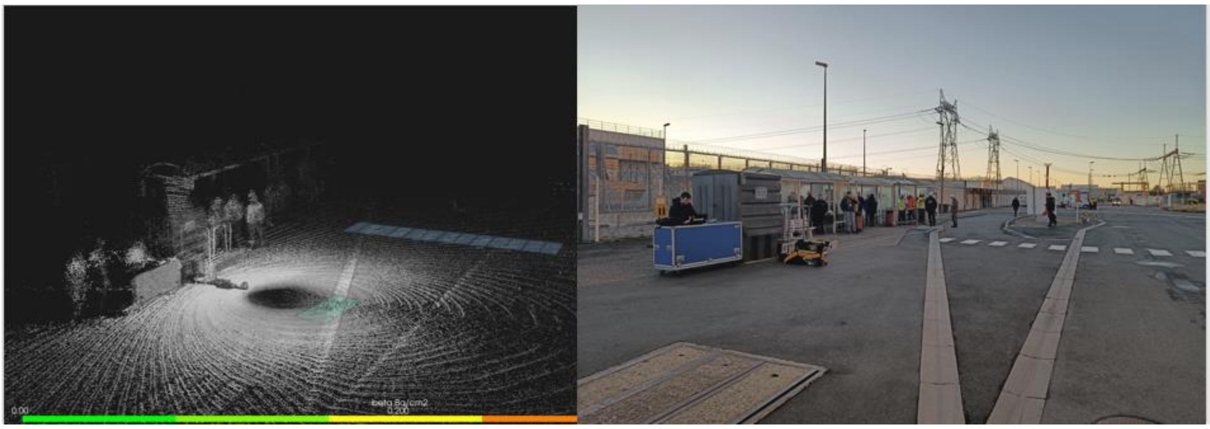

Figure 2 : 3D point cloud of a road clearance for automated clearance with AMORAC

By performing road clearance, some limits of AMORAC have been met: Weather conditions can prevent to deploy AMORAC during heavy rain, and the car traffic is not handled by the current system. Nevertheless, it is under discussion to work around heavy traffic by enabling the robot at nights and low activities periods.

- The NPP uses a buffer area where incoming and outcoming equipment potentially contaminated or active are controlled for contamination or dose. Most controls activities are performed on truck decks, containers, and fuel transportation sarcophagus.

Figure 3 : 3D point cloud of the buffer area for clearance for automated clearance with AMORAC

A full room measurement sequence was conducted for this area. For a threshold of 0.4 Bq/cm², the maximum speed of the alpha/beta sensor movement reached 4 cm/s (suggested from the monitor supplier), however the speed can be individually changed by the operator. The robot was also able to climb on the scaffolding displayed in the right image of Figure 3.

- The following area is a hot equipment storage (used within the plant) inside containers stored on-site. The area's restriction classification level could vary depending on contamination levels of the present equipment.

Figure 4 : 3D point cloud of a container for automated clearance with AMORAC

This test has proven that AMORAC is able to autonomously reach the container 20 meters away from its docking station, inspect the side of a 6 meters long container under light rain. It has detected both hot sources placed on the container handles (bright red squares on the left side of Figure 4 above).

- The fourth use-case showcased the ability of AMORAC to access and perform jobs in complex areas **autonomously**, up to 50m away from the docking station, across multiple stories trough stairs, steel grating and gateways.

Figure 5 : Measurement on various surfaces and equipment

The following table presents the distribution of three manual control types performed at the NPP.

Control type	Percentage
Wiping tests	70 %
Gamma radiation	15 %
Alpha/beta contamination	15 %

Table 1 : Distribution of manual control types

Six full-time employees (per reactor) perform these tests. During reactor outage, up to four additional employees perform manual control measurements. According to Table 1, AMORAC can cover 30 % of control measurements only with its automatic measurement capability, thus validating its relevance on this type of application.

Area	Frequency
Control of every restricted area door, hot equipment storage	• every week in normal operation • every in/out of equipment • at the end of outage
Control of hot workshop: doorstep	• every week
Control of hot workshop: inside	• every 10 weeks (not possible with contamination monitor because of background radiations)
Control of every road on-site	• every 10 weeks

Table 2 : NPP controlled area frequencies

Deployment of AMORAC on a hot base

CEMO is one of Framatome's three hot bases in France. A hot cell is a specialized facility meticulously designed to handle radioactive materials with utmost safety, ensuring comprehensive protection for both operators and the surrounding environment. Daily and monthly checks are required to prove the non-contamination of the facility. It is located at Chalon sur Saone.

As the test program presented in Table 2, specific areas must be controlled frequently and at various frequencies. Clearance measurements require to be done at a specific speed defined by the standard *ISO 7503-1* and depending on the monitor. In this case we are using Berthold LB1343 monitor with a measurement surface of 150 mm x 230 mm (345 cm²) on AMORAC. Nuclides of check sources are Cobalt-60 (Co-60) and Americium-241 (Am-241). At CEMO the minimal detectible value of alpha activity is 0.04 Bq/cm² and beta activity is 0.4 Bq/cm² (background radiation deduced for both values). The monitor speed is set to 0.04 m/s in this configuration.

The following table presents the different areas where non-contamination must be proven and their frequencies of control.

N°	Area	Measurement type	Surface area (m²)	Frequency (per month)	Total area (m²)
1	Parking zone	β	96	50	4,800
2	Container processing area	β	80	22	1,760
3	Inner container	β	12	30	360
4	Truck decks	β	27	50	1,350
5	Outer container	β	36	50	1,800
6	Under container	β	12	1	12
7	Storing area alleys	β	200	1	200
8	Property side wall	β	360	1	360

Table 3 : Controlled areas at CEMO and their surfaces

The next table represents time spent to measure each area depending on the selected measurement speed.

N°	Area	Minimum theoretical time based on ISO 7503-1 (min)	Practical measurement time	Minimum time for AMORAC with LB1343	Minimum theorical measure time (based on ISO 7503-1)	Monthly practical measurement time (min)	Monthly AMORAC measurement time (min)
1	Parking zone	120	204	288	6,000	10,200	14,400
2	Container processing area	100	170	240	2,200	3,740	5,280
3	Inner container	15	26	36	450	765	1,080
4	Truck decks	34	57	81	1,687	2,850	4,050
5	Outer container	45	77	108	2,250	3,825	5,400
6	Under container	15	26	36	15	26	36
7	Storing area alleys	250	425	600	250	425	600
8	Property side wall	450	765	1,080	450	765	1,080

Table 4 : Controlled areas at CEMO and time spent to controlled them depending on the control type

Based on previous values, we can estimate the workload according to the total surface at CEMO to be controlled.

Total control time each month	Minimum theoretical time based on ISO 7503-1	Practical control time	AMORAC measurement time (including charging, walking…)	Unit
	10642			m²
	222	376	532	Hour

Table 5 : Total controlled surface at CEMO and theoretical time spent for contamination characterization

Results provided by both previous tables quantify that AMORAC is slower than practical control. However, the practical control time does not include breaks taken by operators and time spent on other aspects of the measurement process. Operators performing measurements must write down measured values on paper and sometimes mark the surface. AMORAC digitalizes all measured values, generates PDF reports automatically and in addition generates point clouds of the scanned environment used for its localization that could serve many other purposes.

Moreover, human workers and robotic solutions have distinct differences. Humans require regular breaks, such as lunch breaks, to sustain their energy and focus. They are also susceptible to illness, which can impact productivity and variable quality outputs. In contrast, robots can operate continuously without breaks or meals and are not affected by health issues, allowing them to maintain consistent and reliable performance.

However, robot's lack of creativity and complex problem-solving abilities that humans possess shall be considered. This is why AMORAC usage should be focuses on long, repetitive and simple tasks. In this case, the required dexterity for contamination measurements over different hights and angles, the navigation ability into a narrow environment make AMORAC an excellent fit.

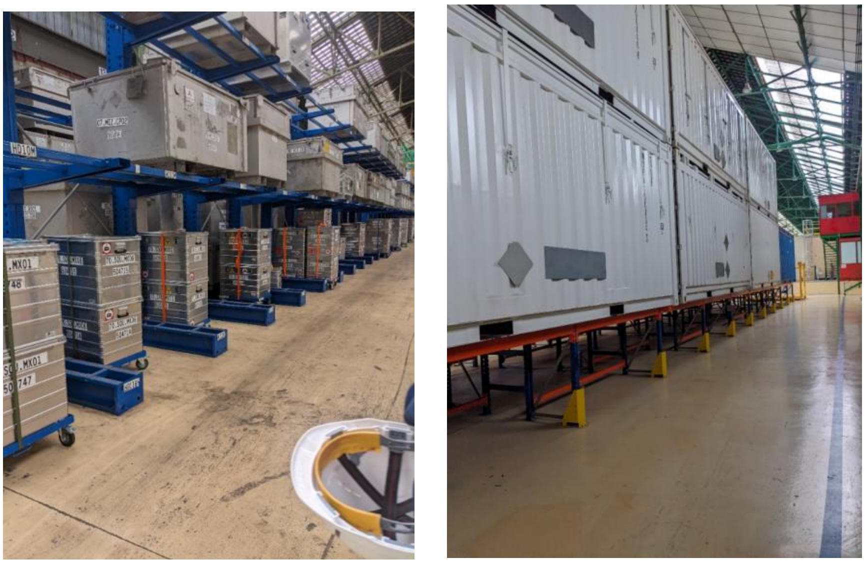

Table 6 : CEMO storage alleys

Intervention in hazardous environment

Since the rise of nuclear energy industrialization in the mid-20th century, the imperative to ensure worker safety and minimize radiation exposure risks has spurred significant advancements in robotics. Environments such as nuclear power plants, radioactive waste storage sites, and accident zones present substantial dangers to human health. In response, engineers and scientists have developed specialized robots capable of operating in these hazardous conditions [1].

A notable example of this is the Chernobyl disaster in 1986, where robots were deployed to assist in the cleanup efforts. These machines were tasked with removing radioactive debris and conducting inspections in areas too dangerous for human presence. Although some early robots faced challenges due to the intense radiation levels, their deployment marked a pivotal moment in demonstrating the potential of robotics in nuclear crisis management. Over time, robotic technology has evolved significantly, giving rise to increasingly agile and sophisticated machines. Modern robots are now capable of navigating complex environments with great dexterity, thanks to research and technology advancements. These developments enable robots to perform tasks autonomously, thereby reducing the need for direct human intervention and minimizing radiation exposure risks for workers. The next table provides a quick overview of robots used in nuclear applications over past decades until now [1][4].

Robot name	RRV-1	ROBUG III	MARS-A & MARS-T	Spot® X-Lab version	Spot® AMORAC version
Purpose	Exploration in reactor basement	Generally unstructured environments	Open and close doors and valve	Close valves	Mapping of contamination measurement
Dimensions	1270x734 483	1000x700x17	/	1100x500x620	
Propulsion	Six wheels	Eight suction legs	/	4 legs	
Energy source	Wired	Wired	Wired	Battery	
Control	Wired	Wired	Wired	Wireless	
Mobile capacities	35° slopes	Walls and flat to rough surfaces	40° slopes	30° slopes, object avoidance, 30 cm obstacles	
Radiation conditions	25 mSv/h to 10 Sv/h	Supposed up to 1kGy	Up to 10 Sv/h (for few hours)	Up to 45 Sv/h	Up to 100 mSv/h
Deployment	Three Mile Island	Response to Chernobyl accident	Pre-accident development	Darlington CANDU Unit	CEMO, multiple NPPs
Year	1984	1995	2002	2023	Since 2022

Table 7 : Deployed robot on nuclear facilities over past decades

Operating in hazardous environment in nuclear facilities while preserving human safety during radiation exposure found its response since the use of nuclear energy by deploying remote operatable robots. These become the embodiment of operators by retrieving visual feedback of the scene, data from different kind of sensors and the ability to interact physically with the environment using multi-axis arms [3].

Robotic systems that can provide information about unknown (geometrically and environmentally) or inaccessible areas can be highly beneficial mentioned by Ioannis Tsitsimpelis et al in 2019 [1]. We could possibly think of virtual reality, to enhance operator proprioception when controlling manually the robot during hazardous tasks where safety is a first concern using recent algorithm of volume rendering techniques, which could drastically increase operation precision and reduce the time required for preparation.

Robots presented in the above table (except Spot®) were fully designed and built by the users from the mechanical part to control command part. Nowadays, modern robots can be easily purchased and customized for various applications, eliminating the need for extensive, application-specific development. This advancement enables businesses to implement robotic solutions without requiring deep expertise in the field or a substantial budget for development, as they no longer need to invest heavily in the foundational mobile base. A company's main development is now reduced to additional payloads design to perform a specialized task.

Conclusion

Spot® from Boston dynamics, an agile quadruped and versatile robot operating without failure up to 413 rem of gamma radiation [4]. Framatome added an automation layer to perform radiological contamination measurements, significantly enhancing efficiency and safety in hazardous environments, bringing to birth AMORAC. By automating repetitive and long-term tasks as clearance measurements in nuclear power plant and hot bases, the need for repetitive human involvement is minimized, thereby reducing the risk of dangerous radiation exposure to personnel [2]. The solution, with its ability to navigate complex terrains, ensures a thorough and precise contamination assessments, ultimately contributing to a safe and efficient operation of nuclear facilities.

The integration of AMORAC, a multipurpose robot capable of performing both high-risk interventions and routine tasks, such as radiological measurements and helps to face challenges associated with hiring qualified personnel presents significant added value. Such a robot not only enhances operational efficiency by seamlessly transitioning between diverse functions but also ensures that critical tasks are executed with precision and reliability. The ability to conduct radiological measurements regularly ensures continuous monitoring and safety compliance, which is crucial in environments where radiation levels must be meticulously managed. Furthermore, having a robot readily available for urgent needs provides an invaluable resource for emergency response, allowing for rapid deployment in situations that require immediate attention. This dual capability not only optimizes resource allocation but also enhances the overall safety and preparedness of the facility, ultimately contributing to a more resilient and adaptable operational framework.

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