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CLEANDEM, a Cyber physicaL Equipment for unmAnned Nuclear DEcommissioning Measurements

Maugan MICHEL[1,*], Guillaume AMOYAL[1] and Vincent SCHOEPFF[1], on behalf of the CLEANDEM consortium
[1]Paris-Saclay University, CEA, List, Palaiseau, France
(*) maugan.michel@cea.fr

Abstract—**Human intervention is still required nowadays for most operations conducted during the Dismantling & Decommissioning (D&D) steps, which cover a wide range of radiological conditions: from the harsh initial conditions, nearly identical to when operating, to the final decommissioning steps where radioactivity has been removed.**

The goal of the three years EU-funded CLEANDEM project, led by CEA List, is to deliver a unique platform which will support the end-users' operations, from the initial radiological assessment to the final characterization of the facility, while enabling their continuous monitoring during the D&D operations.

Ten leading actors from four European countries' nuclear industry and research, have joined their expertise and efforts in the CLEANDEM consortium to develop a mobile unmanned ground platform (UGV), equipped with upgraded highly-mature detection technologies for 3D-localized radiological measurements. These will complete the facilities' available data into a 3D and fully detailed Digital Twin of the surveyed area, thus improving the planning and traceability of the D&D operations.

Keywords — **Dismantling & Decommissioning, Euratom, Radiation Protection, Gamma imaging, Radiological mapping, Contamination monitoring, Shape-sensing, OSL, Distributed dose measurement, UGV, Robot, Autonomous navigation and Localization, SLAM, LIDAR, Digital Twin, Training, In-situ demonstration.**

I. INTRODUCTION

THE CLEANDEM consortium, led since its kick-off in March 2021 by CEA List, gathers the expertise from European nuclear industry (CAEN, ORANO DS, ANSALDO, RINA, TECNALIA, SOGIN, AiNT) and research (CEA List, INFN, ENEA), to address one of the limitations in the field of Dismantling & Decommissioning (D&D), which is the radiation exposure of human operators at the different steps of the operations.

Until the ADARA principle (As Decomissionable as Reasonably Achievable) is widely implemented during the design phase of nuclear facilities, significant improvements could be achieved during these phases regarding human exposure to ionizing radiation, the duration of operations and their cost.

Obviously, any operation that can be achieved remotely will reduce the dose uptake of operators and improve their safety. Consequently, following the advancements in robotics capabilities over recent years, a significant focus of interest for the stakeholders is the utilization of robots to be integrated in D&D operations. Also, whereas battery autonomy keeps on increasing, the power consumption of the embedded equipment also will decrease the available time for remote operations. Both subjects are actively researched and developed to achieve cheaper, faster, and safer D&D.

Reducing the dose uptake, time and cost of operations are addressed in CLEANDEM by improving the radiological assessment continuously undertaken during D&D: from the initial characterization (often synonymous of high-dose rates), to the final characterization where all radioactivity has been removed, with the update following every clean-up action undertaken in the meantime. The proposed solution aims at upgrading existing radiological measurement systems, with Technology Readiness Levels (TRL) ranging from 5 to 7, and embedding them on an Unmanned Ground Vehicle (UGV). The 3D reconstruction of the environment, required for the autonomous localization and navigation of the UGV, are sent along with the radiological measurement, by the robot, to build and/or update the Digital Twin of the facility. The latter, containing all available radiological data (legacy as well as those updated with the sensors), can then be used to track past and plan future D&D operations.

The work achieved by the consortium, will be presented infra following their division in the different Work Packages (WP), addressing:

- specifications' collection from the stakeholders to define the Concepts of Operations (WP2 "CONOPS")
- improvement of low-cost sensors for rapid neutron and gamma and distributed gamma dose rate mapping, as weel as gamma spectro-imaging (WP3).
- neutron/gamma detection and identification sensors improvements (WP4);
- air and surface contamination monitoring (WP6).
- unmanned modular mobile platform equipped with a robotic arm (WP7);
- data fusion and Digital Twin development.

Also, two additional WPs are dedicated to estimating the social and economic impact of the UGV platform on the market (WP5), and on the concept for the training programme and the system's final demonstration for CLEANDEM's end-users network (WP9).

The overview of the CLEANDEM solution is presented in Fig. 1.

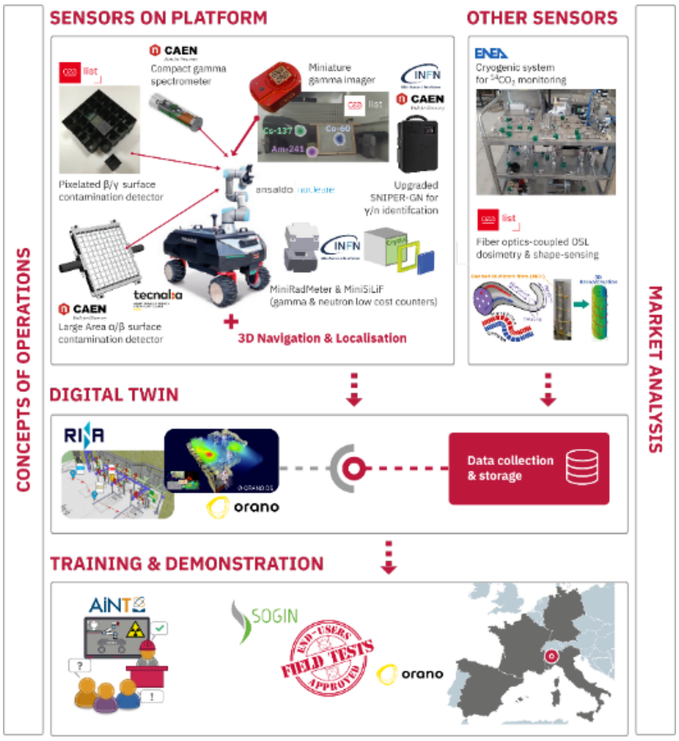

Fig. 1: overview of the CLEANDEM solution.
Sensors on platform: Pixelated β/γ surface contamination detector (CEA List), Compact gamma spectrometer (CAEN), Miniaturized gamma imager (CEA List), Upgraded SNIPER-GN for γ/n identification (CAEN and INFN), MiniRadMeter & MiniSiLiF (gamma & neutron low cost counters, INFN), Large Area α/β surface contamination detector (CAEN). Robotnik's RB-VOGUI platform with a Universal Robots' UR 5e robotic-arm (TECNALIA and ANSALDO respectively).
Other sensors: cryogenic system for $^{14}CO_2$ monitoring (ENEA) and fiber optics-coupled OSL dosimetry & shape-sensing (CEA List).
Digital Twin with PoStLAM (RINA and ORANO DS) and **Training** (AiNT) **and Demonstration** at the ENEA Casaccia facility (SOGIN).
Work Packages **Concepts of Operations** and **Market Analysis** operate in parallel to the others.

II. CONCEPTS OF OPERATIONS (WP2)

During the first months of the project, ORANO DS has been in charge of delivering the input information necessary for the technical developments to be set on their respective tracks. These information were defined following interviews with multiple stakeholders and operators of D&D to write the Technical Specifications expected from the final system developed by the consortium. With the help of SOGIN, ORANO DS was able to establish the base of the D&D scenarios to which the CLEANDEM robot shall be able to address, each considering different phases of the operations (early, day-to-day and final characterization).

A third deliverable which is a European Guideline for D&D Operation containing a list of recommendations for different case of D&D operations specific to robotic operations for radiological monitoring shall be available to the public at the end of the project to benefit from the consortium's experience gained from the project.

III. LOW-COST SENSORS FOR RAPID NEUTRON, GAMMA AND DISTRIBUTED DOSE RATE MAPPING (WP3)

Three families of sensors are developed within the frame of WP3. The first one is a low-cost quick dose-rate monitor by INFN, combining the MiniRadMeter (miniature gamma counter/spectrometer) and MiniSiLiF (miniature neutron counter). Shown in Fig. 2, the MiniSiLiF uses a ^{6}LiF slow neutrons converter layer after they have been slowed down by the moderator (6 cm × 6 cm × 6 cm polyethylene box), taking advantage of the

$$^{6}\mathrm{Li} + n_{slow} \rightarrow {}^{7}\mathrm{Li} \rightarrow \alpha + {}^{3}\mathrm{H}$$

reaction, where either alpha or triton particles are detected by a silicon diode. In case one were only interested in thermal neutrons, the moderator can be removed leaving the bare SiLiF detector in operation [1].

The selected scintillator for gamma detection is a CsI(Tl) coupled to a Silicon Photomultiplier (SiPM). The scintillator choice is based on its high-quality detection properties in terms of detection efficiency (i.e., high density), light yield, and energy resolution at a reasonable cost [1].

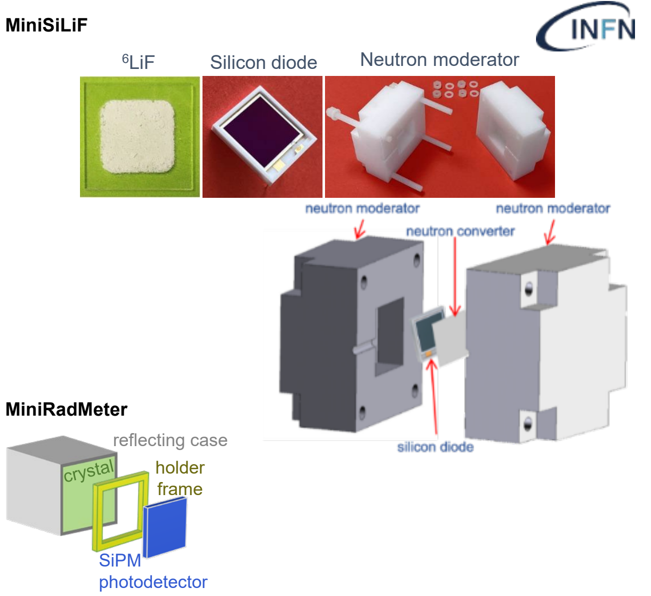

Fig. 2: parts and exploded 3D view of the INFN's MiniSiLiF neutron counter and exploded view of the MiniRadMeter (CsI(Tl) crystal).

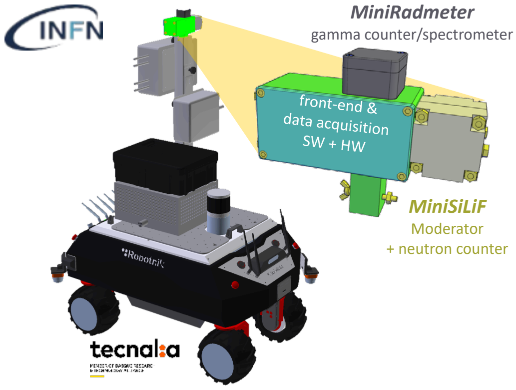

Fig. 3: MiniRadMeter and MiniSiLiF mounted on the robotic platform.

The results and detailed charateristics for both sensors have been published in [1].

The second system within WP3 is CEA List's Nanopix, currently the smallest coded-aperture gamma imager in the world (10 cm × 7 cm × 5.5 cm). Shown in Fig. 4, it's low weight (412 g) allows it to be mounted on the robotic arm and scan in any direction to localize gamma hotspots. Coupled with a miniature RGB camera, it combines the visible image with the post-processed data from a pixellated Timepix sensor to produce the superimposition of both images with spectrometric information of the source, as visible on the right in Fig. 4. It is also shown in a preliminary mounting configuration on the robotic arm in Fig. 7. A soon-to-be-addressed challenge will be the integration of Timepix3 technology to Nanopix for improved performances.

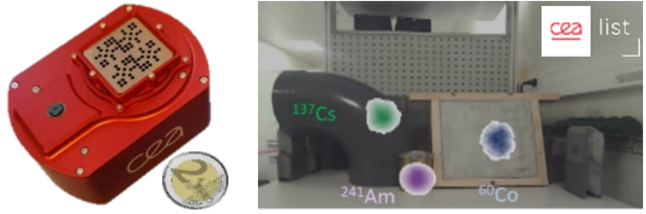

Fig. 4: Nanopix gamma spectro-imager and demonstration of the hotspots localization capabilities using different radionuclides (^{137}Cs in plastic pipe, ^{241}Am in steel drum and ^{60}Co behind 2 cm of concrete).

The last of the developments within this work package, one of the two which are not not to be mounted on the robot, is the joint use of Optically Stimulated Luminescence (OSL/FO) dosimetry and optical fiber shape sensing. The final aim of this innovative approach for D&D applications is to gather both topographic and radiological data within hard-to-access and hidden zones useful for 3D reconstruction using Monte-Carlo (MC) codes. OSL/FO dosimeters are small enough to be pushed through existing access in order to provide radiological investigation in hard-to-access zones while sparing heavy duty that would otherwise be necessary to give access to conventional dosimeters. However, the geolocalization of the miniature OSL/FO detectors is still based on original drawings that are often erroneous or even unavailable or lost. Shape sensing is a solution likely to provide missing topographic data and ensure proper 3D reconstruction to be made.

Shape sensors are already used in medical applications on short length (< 1 m) [2–3]. The CLEANDEM development aims to use shape-sensing concepts (materials, methods and algorithms) for D&D applications and to check their compliance with their specifications, particularly long-range monitoring (typically up to 10 – 13 m) and radiation hardness.

Fiber Optic Shape Sensing (FOSS) is a cutting-edge optical fiber sensing technology that employs a fiber-based flexible cable to follow the 3D shape of an object in real time without requiring eye contact. It consists in the ability to dynamically track position and shape of any point on an optical fiber cable in 3D space, relying upon bending-induced strain along multicore (MC) fibers or special cables made of several single mode fibers. Longitudinal strain profiles are recorded along each fiber core and an algorithm reconstructs the shape of the cable using strain profiles as input data. The shape sensing within CLEANDEM relies on a 7-core Multi-Core Fiber (MCF, where six fibers are evenly distributed around one). The latest results, shown in Fig. 5 (right), achieve shape reconstruction over a length of 6.2 m.

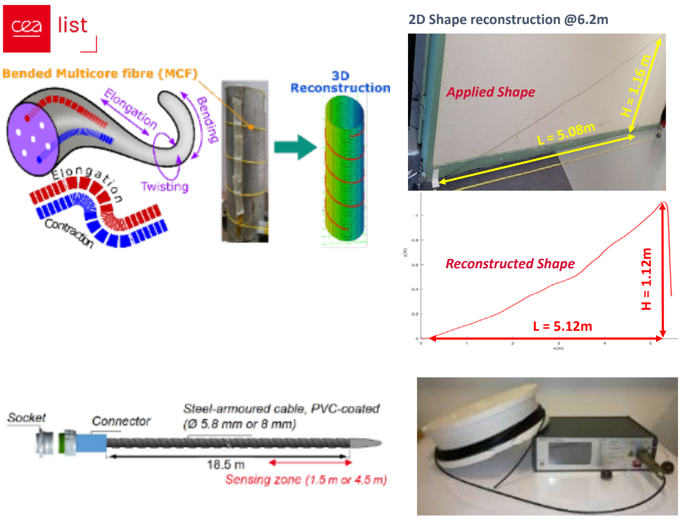

Fig. 5: (top) principles of shape-sensing with 3D shape and recent 2D shape reconstruction of a 6.2 m MCF and (bottom) probe design and INSPECT OSL/FO readout-unit designed by the CEA List within the PIA-Andra INSPECT Project.

IV. THE NEUTRON/GAMMA DETECTION AND IDENTIFICATION SENSORS (WP4)

The second sensors-dedicated work package includes the Sniper GN and Gamon systems from CAEN which will be mounted on the robot and the development of a compact sensor to be mounted on the robotic arm.

The Sniper GN for gamma and neutron measurement is composed of a 38 mm × 38 mm $CeBr_3$ crystal and a 51 mm × 51 mm stilbene scintillator. Whereas the NaI(Li) from the Gamon is able to achieve both gamma spectrometry and neutron detection using Pulse Shape Discrimination (PSD) with one device; it achieves it with a lower gamma energy resolution than the $CeBr_3$. But it's combination with the Sniper GN allows for better gamma/neutron mapping with the ability to identify radionuclides based on the neutron gamma ratio they exhibit (see Fig. 6).

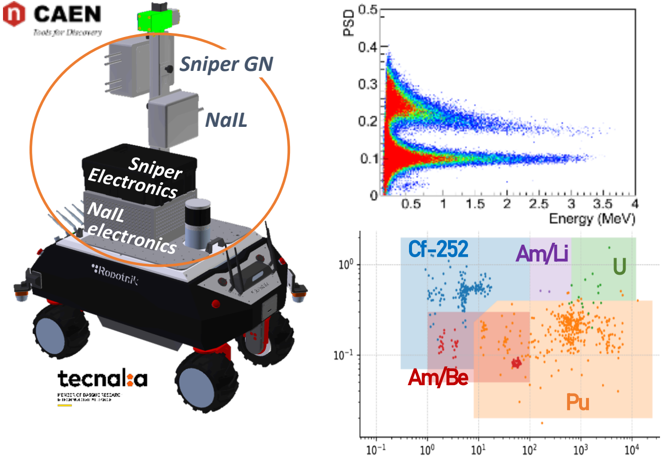

Fig. 6: CAEN's Sniper GN ($CeBr_3$ and stilbene scintillators) and Gamon (NaIL™ scintillator) mounted on the UGV (left) and example of gamma pulse-shape discrimination (top right). The latter, in combination with neutron measurement, enables to identify Nuclear Materials (bottom right) even when hidden behind gamma or neutron shielding.

Shown in Fig. 7, the last sensor developed within WP4 is a large volume hemispheric CZT detector to be mounted on the arm (probe size: L × diam. = 12 cm × 5 cm). Following hotspot localization (eg. from the Nanopix gamma spectro-imager), it will enable a deeper gamma inspection during the first step of the survey and be have to access places harder to reach for larger sensors.

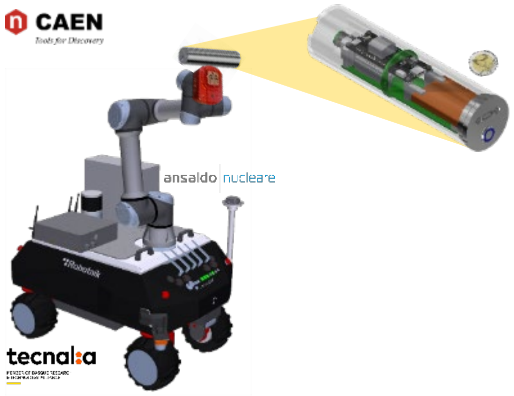

Fig. 7: preliminary mounting configuration of the compact CZT sensor (CAEN) and Nanopix (CEA List) on the UR 5e robotic arm (Universal Robots).

V. AIR & SURFACE CONTAMINATION MONITORING (WP6)

Two large surface contamination monitors are developed within CLEANDEM by CAEN and CEA List, respectively measuring alpha/beta and beta/gamma particles. The last system, developed by ENEA is in charge of monitoring radiocarbon dioxide ($^{14}CO_2$).

Whereas CAEN's large surface (576 cm^2) PSD phoswich contamination monitor is capable of α/β/γ measurement, this goes with heavy shielding (50 kg) and scintillator. Considering the β/γ capability of CEA List's system, the development was refocused on an α/β-dedicated system to benefit from this complementarity; thus allowing both systems (α/β and β/γ) to be mounted on the robotic arm. The 25 µm ZnS(Ag) coating (alpha detection) is coupled to a PVT scintillator (β detection), and both are coupled to a lucite light guide leading to the photomultiplier. Because the area of the sensor affects the light output and because working in coincidence also reduces noise level, it was chosen a geometry with two photomultiplier tubes (PMT) on opposite sides, as visible in Fig. 8.

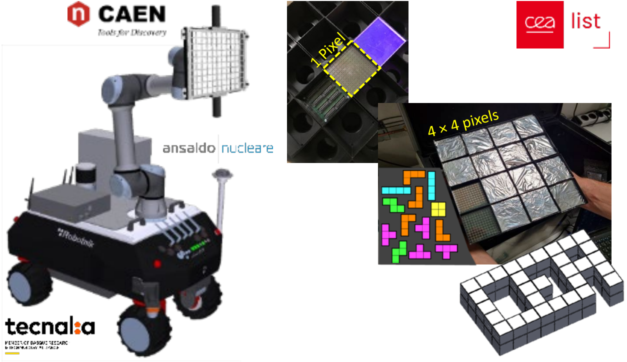

Fig. 8: CAEN's large area α/β PSD phoswich mounted on the robotic arm and CEA List's pixelated plastic scintillator (also to be mounted on the arm).

Also shown in Fig. 8 and based on PSD of phoswich scintillators, CEA List's β/γ system is made of 5 cm × 5 cm plastic scintillators inside a frame which can then be assembled as needed to fit the measured surface. Each scintillator, coupled to a SiPM and readout electronics are mounted on springs to allow them to adapt for the scintillator to be as close to the surface as possible, even if it is uneven.

VI. UGV EQUIPPED WITH A ROBOTIC ARM (WP7)

Following the definition of Concepts of Operations and technical specifications, the first major equipments to be purchased were the the robotic arm and, above all, the unmanned robotic platform on which it has to be mounted. From the conclusions of WP2, Tecnalia and Ansaldo Nucleare respectively selected Robotnik's RB-VOGUI+, i.e. the RB-VOGUI visible in Fig. 9 equipped with Universal Robots' UR-5e robotic arm.

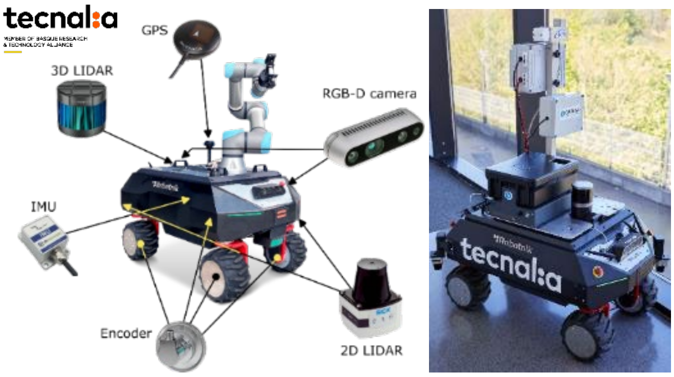

Fig. 9: (left) RB-VOGUI (Robotnik), and sensors used by Tecnalia to achieve autonomous navigation and localization of the platform. The platform's dimensions are 104 cm × 65 cm × 56 cm.
(Right) photograph of the UGV with the MiniSiLiF, MiniRadMeter (INFN), and Sniper GN and Gamon (CAEN) and their electronics, shown in Fig. 3 and Fig. 6.

In charge of the robotic arm and the interfacing of the sensors mounted on it, Ansaldo Nucleare and Tecnalia manage the data collection from the different sensors developers with the necessary connectors and communication protocols to allow their unhindered transfer to RINA, in charge of data fusion and the Digital Twin.

VII. THE DATA FUSION AND DIGITAL TWIN DEVELOPMENT (WP8)

The last technological development, led and achieved by RINA, is the fusion of all data and their combination in the Qpro² Multiplatform to build a Digital Twin (DT). The DT design aims at providing a unique tool able to collect and display (in 3D format) all the useful data for D&D operations acquired from different data sources (sensors, materials samples, legacy database, etc.), as shown in Fig. 10. It also considers the definition of a grid for the chemical and radiological classification of waste. Still under development, its objectives are to achieve direct monitoring of the raw data acquisition to generate alarms and warnings in case of deviation, to represent acquired data as a dashboard and as a 3D representation directly in the plant model, definition and representation of suitable indicators, analysis of the legacy data. Its last and not least functionality is to support D&D decisions in defining strategy and scenarios.

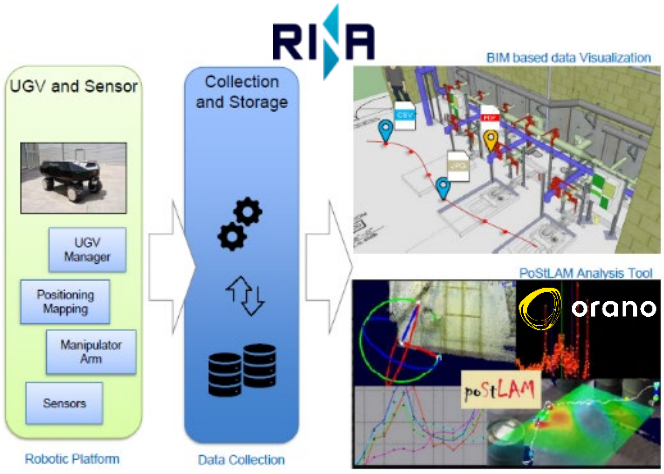

Fig. 10: Functional representation of data flow in data acquisition approach.

To achieve higher-level radiological data post-processing and better exploit 3D point clouds with positioned radiological data to prepare interventions, Qpro^2 is combined with ORANO's PoStLAM software. Based on the 3D rendering of the area built by the robot, it can display a radiological map overlay for better visualization, as well as, using avatars, to anticipate dose uptake by the operators and improve the scenario of human intervention regarding the ALARA principle. The overlay and avatar positioning in a 3D reconstructed scene are shown in Fig. 11.

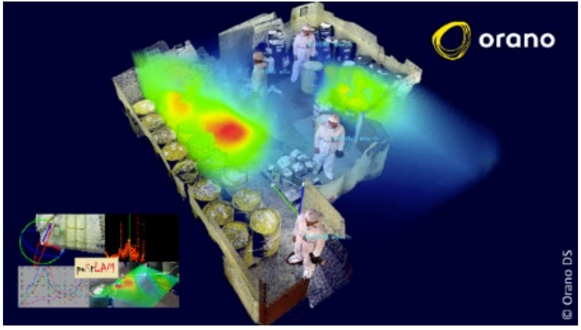

Fig. 11: overlay and avatar positioning in a 3D reconstructed scene in PoStLAM (ORANO).

VIII. TRAINING AND DEMONSTRATION (WP9)

Led by SOGIN, this work package is in charge of the training of end-users (AiNT) as well as the in-situ demonstration of the technical developments emerging from the project (SOGIN)

Aachen Institute for Nuclear Training (AiNT) is in charge of developing, test a training programme in close collaboration with the other partners of the consortium, as well as with CLEANDEM's End-Users Network (operators, stakeholders, etc.), as each user may have specific requirements and therefore the training needs to be customized accordingly. Following the CONOPS, AiNT established the training programme concept and organized two webinars for the End-Users Network, where the CLEANDEM developments were presented and feedback from the participants analyzed in order to pinpoint their needs. Once the training programme evaluated, AiNT will carry the training out to end-users.

The CONOPS having been established with different realistic scenarios, different sites were identified by SOGIN to host the in-situ demonstration of the final systems developed by WP3, WP4, and WP6–8, with the aim to demonstrate their combined capability to:

- measure in hard to access areas with remote solutions;
- give real time information on the facility status;
- perform the initial radiological characterization of an area (in presence of hot spots and very low contamination level).

In coordination with the consortium, a facility of the EUREX Saluggia plant was selected to demonstrate the capabilities of the final systems. One the areas identified to run the final demonstration is shown in Fig. 12.

Fig. 12: photograph of the host location for the final in-situ demonstration of the CLEANDEM developments.

IX. MARKET & COSTS ANALYSIS (WP5)

Led by CAEN, this working group, including ORANO and SOGIN, is focused on the social and economic impact of the UGV platform on the market. The impact based on nowadays used technologies has to be evaluated then compared to the impact based on the UGV platform and the digital twin performances. The effectiveness of the platform will be estimated thanks to the use cases described in the CONOPS.

To do so, WP5 has developed a comparative database of the existing or commercially available and the innovative technologies identified in the CLEANDEM consortium; as well as an evaluation methodology useful for decommissioning cost estimation based on different scenario approaches (business cases).

The cost analysis of the robot on different business cases and extraction of market performance indexes shall be completed in the near future.

X. CONCLUSIONS

The developments undertaken by the CLEANDEM consortium have been presented, along with how they are implemented in order to build a Digital Twin with radiological mapping capabilities, to reduce the time and cost of D&D operations, and the dose uptake by human operators, which is a major interest of stakeholders.

Now nearly two and a half years out of the three of the project, most technological developments are over and the consortium is preparing the final field tests for late 2023, before the final workshop at the EUREX Saluggia site, expected early 2024.

ACKNOWLEDGMENT

The still ongoing aftermath of the international sanitary crisis and the ensuing shortage in multiple areas of manufacturing could have induced major delays in the different developments of CLEANDEM. The authors are very grateful to the consortium members and end-users who made it possible to stay on par with our common goal, thanks to their proactivity, dynamism, critical thinking and support.

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