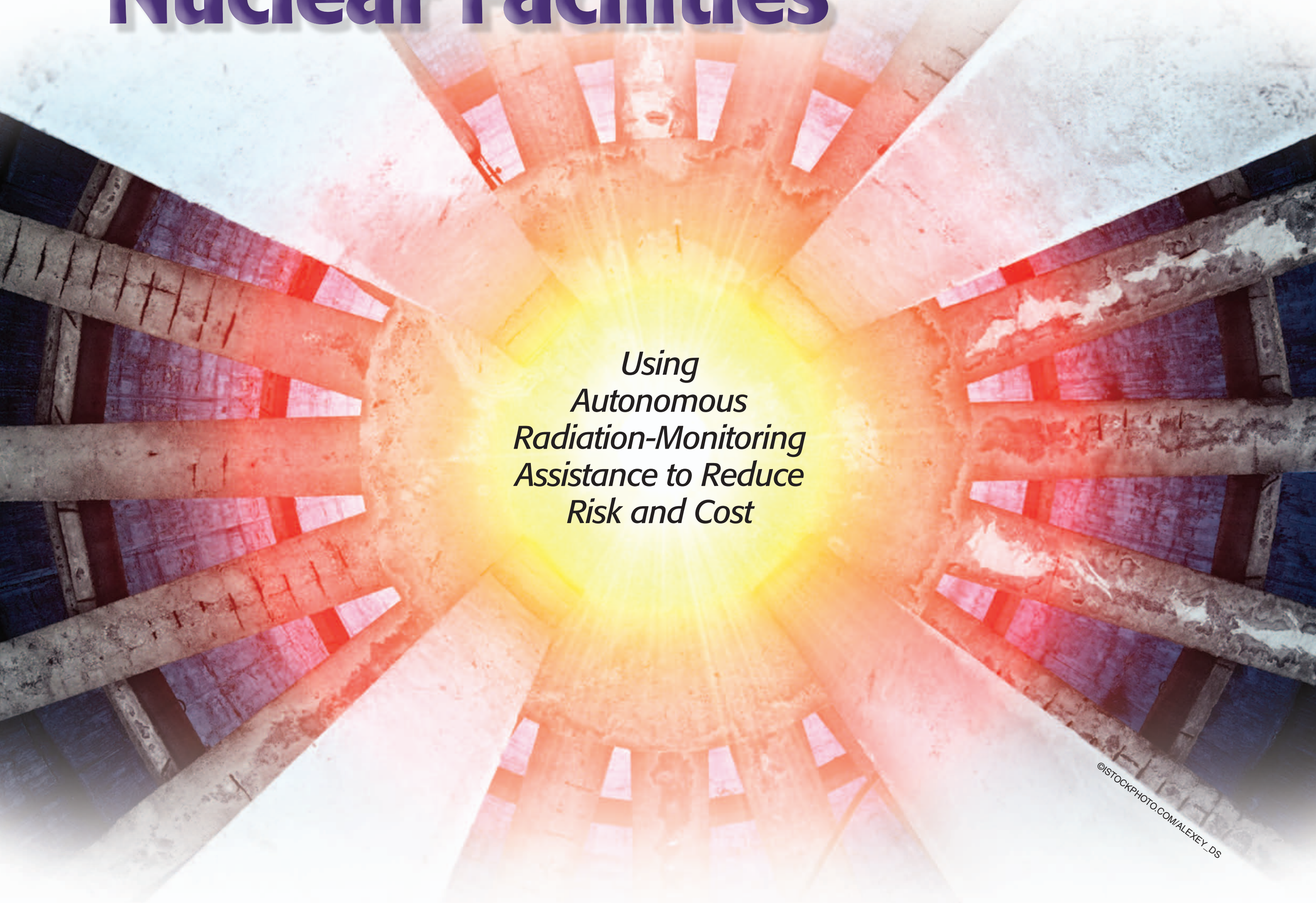
A Robot to Monitor Nuclear Facilities



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Using Autonomous Radiation-Monitoring Assistance to Reduce Risk and Cost

By Benjamin Bird, Arron Griffiths, Horatio Martin, Eduardo Codres,
Jennifer Jones, Alexandru Stancu, Barry Lennox, Simon Watson,
and Xavier Poteau

Nuclear facilities often require continuous monitoring to ensure there is no contamination of radioactive materials that might lead to safety or environmental issues. The current approach to radiological monitoring is to use human operators, which is both time consuming and cost inefficient. As with many repetitive, routine tasks, there are considerable opportunities for the process to be improved using autonomous robotic systems.

This article describes the design and development of an autonomous, ground-based radiological-monitoring robot, Continuous Autonomous Radiation-Monitoring Assistance (CARMA), and how, when it was deployed in an active area at the U.K.'s Sellafield nuclear site, it detected and located a fixed α source embedded into the floor. This deployment was the first time that a fully autonomous robot had ever been deployed at Sellafield, the largest nuclear site in Europe.

Expanding Efforts in an Increasingly Important Field

Monitoring nuclear facilities and rapidly identifying any spread of radiological materials is of global concern.

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Worldwide, there are 448 operational nuclear reactors, with a further 61 under construction. In addition, there are 158 reactors in shutdown awaiting decommissioning as well as 180 research reactors and critical assemblies also being decommissioned. Approximately 273,000 tons of spent fuel from reactors are currently in storage—an amount that increases by almost 7,000 tons per year [1]. Most, if not all, of these facilities will require some form of radiological monitoring, whether continuous, such as in operational nuclear plants, or periodic, as in waste storage facilities [2]. Current monitoring technologies consider airborne/surface contaminants and worker dosimetry, and the sensors are either fixed point, handheld, or worn by operators.

Since the Fukushima Daiichi incident in 2011, the use of mobile robots for characterizing and monitoring radiological sites has increased significantly.

There are three types of ionizing radiation that typically need to be monitored: alpha (α), beta (β), and gamma (γ). Alpha particles are the most ionizing and are generated by heavy elements, such as uranium, or transuranic elements, such as plutonium. They can be stopped by a sheet of paper and are only dangerous to humans if ingested. Beta radiation is more penetrative than α and is generated by a range of radioactive elements, but it is less harmful and still straightforward to shield against. Gamma radiation is a higher-energy electromagnetic wave that is highly penetrative. It is the hardest to shield against, and personal dosimeters worn by nuclear workers are used to measure exposure to it [3].

Perhaps surprising is that the detection of α contamination presents the greatest challenge: α radiation has low permeability in air, and so any detector must be placed within a few centimeters of the source for a short period of time to ensure reliable detection. This is both extremely time consuming when monitoring large areas manually and also relies heavily on operators being diligent during their surveys. Beta and γ radiation, having greater permeability in air (β less than γ), can be detected at a distance, although the technology to identify the precise location of any source materials is an important area of active research [4].

Case Study: Radiological Monitoring at Sellafield

The Sellafield site is the primary storage point for the United Kingdom's nuclear waste. The country has 170 major nuclear facilities, all of which will be decommissioned over the next century. These facilities include legacy plants and laboratories, as well as interim storage areas. In these areas, monitoring known α sources and β and γ fields and identifying any spread of contamination are of considerable importance.

On the Sellafield site, radiological monitoring is undertaken by the Health Physics team as part of the Environmental, Health, Safety, and Quality group. The team's role is to ensure that the As Low As Reasonably Practical policy is applied and that personnel are protected from the harmful effects of exposure to ionizing radiation. To ensure this, Health Physics personnel regularly monitor facilities and equipment for contamination. Areas are manually surveyed using approved commercial, off-the-shelf handheld monitors. The areas surveyed can vary from roads and buildings to people and involve packages being transferred between active and nonactive areas.

Benefits of Autonomous Systems

Enhancing Health Physics' capabilities by upgrading the current manual surveys to more autonomous methodologies would increase productivity and reduce risk and cost. In addition to these general benefits, the use of mobile autonomous robots could provide more specific gains:

- Automating the collection of dose rate or spectrometric data would allow Health Physics personnel to complete other tasks, such as more complex surveys, data interpretation, and systems maintenance. CARMA has been designed to survey floor spaces in relatively simple environments, such as corridors and open spaces with limited clutter. Laboratories, for example, represent a much more complex challenge, as they can require surveys at multiple heights, inspection of cupboards and drawers, and so forth.
- Automatic archiving of the results, with positional data, in a readily accessible format would enable any changes in radiological information (e.g., dose rate and species) to be identified quickly and clearly.
- Robotic systems can be designed to ensure that detectors are held at a fixed distance above the area being monitored, thus improving consistency in survey data. This is particularly important for the detection of α contamination but is difficult to reliably achieve manually.

Mobile Robots for Nuclear Environments

Since the Fukushima Daiichi incident in 2011, the use of mobile robots for characterizing and monitoring radiological sites has increased significantly. The primary application areas for such systems are future incident response, gaining access to areas where human entry may be restricted because of safety concerns, and large-scale monitoring of open spaces [5], [6].

The majority of mobile robots developed for radiological characterization of the Fukushima Daiichi facilities have focused on γ radiation inspections [7]. Robots such as the JAEA-3 [6] and Quince [7] have been deployed in the Fukushima facilities to conduct γ surveys. Although each of these robots has been teleoperated, their deployment into radiologically active environments has increased the nuclear industry's confidence in robotic systems.

The use of remote, mobile radiological-inspection robots is also being considered for more routine scenarios. The RICA [Robot d'Inspection pour Cellules Aveugles (blind cell inspection robot)] robot, which was developed by the French Alternative Energies and Atomic Energy Commission and Cyberia in France, has been deployed into operational nuclear facilities to conduct γ inspections [8]. A set of corobots has also been developed at the Georgia Institute of Technology to detect and localize γ and neutron sources embedded in floors [9]. However, no robots seem to have been developed for the autonomous detection of α contamination [10].

This article describes the design and testing of a mobile robot that can be used for autonomous radiological inspections. The CARMA robot was developed by the University of Manchester in direct collaboration with Sellafield Ltd. and is able to conduct α and β/γ inspections. The platform was successfully used to survey facilities at the University of Manchester as well as on the Sellafield site, where it was shown to be able to autonomously survey a facility and locate a known source of α contamination.

The CARMA Platform

The CARMA platform was initially developed to conduct radiological inspections of floor areas within legacy and operational nuclear facilities. It is a proof-of-concept robot that aims to showcase the use of autonomous robots in noncritical nuclear environments. It was designed specifically to conduct short-duration scans (up to an hour) and to detect and locate spots of contamination within the scanned area. These scans require geometric and radiological maps to be generated with a resolution of approximately 5–10 cm. The robot was developed to operate indoors in smooth, flat areas, such as corridors, offices, and laboratories. Figure 1 shows the robot, and Table 1 presents the specifications.

The CARMA platform is a modified TurtleBot 2 equipped with a sensor package containing an α/β sensor (Thermo Fisher Scientific DP6) for α-source floor monitoring and detection and two personal γ dosimeters (Thermo Fisher Scientific RadEye), which can be used as a high-sensitivity γ radiation detection and dose rate measurement tool. These detectors were specified by Sellafield Ltd. and match the equipment it currently uses in its handheld instruments.

The DP6 sensor is fixed at a height of 10 mm above the floor using a spring arrangement, which allows the sensor to move over uneven surfaces while maintaining the separation distance. One effect of not maintaining a fixed height above the floor is reduced accuracy for the estimated dose rate, which can be overcome by keeping the sensor over areas of interest for 20–30 s.

To ensure an accurate reading, the DP6 sensor head must be over a target area for at least 1 s. The sensor head has dimensions of $160\ \text{mm} \times 80\ \text{mm}$, which means that the maximum forward velocity is restricted to between 0.1 and 0.2 ms^{-1}, depending on its orientation. The resolution of the measurements is an $80\ \text{mm} \times 80\ \text{mm}$ area, with a positional accuracy of ± 100 mm.

The CARMA robot logs the data from the DP6 sensor, but the analysis is completed offline. The activity-level thresholds for the identification of radiation contamination areas are preprogrammed by the operators. These can be varied depending on the operating environment and type of deployment. The target operational environments are areas where humans can already conduct manual monitoring, so the air dose rates are negligible. However, the characterization of some standard components with the effects of γ radiation suggests they can withstand a total ionizing dose of up to 1,000 Gy [11].

A single 2D lidar (with a range of 4 m), a depth camera, and three infrared (IR) sensors were integrated onto the platform to enable autonomous navigation. CARMA uses the Robot Operating System (ROS), a widely used open-source middleware that simplifies the control of robotic systems and the integration of their subsystems. The ROS framework allows the robot to be operated in either manual or autonomous mode.

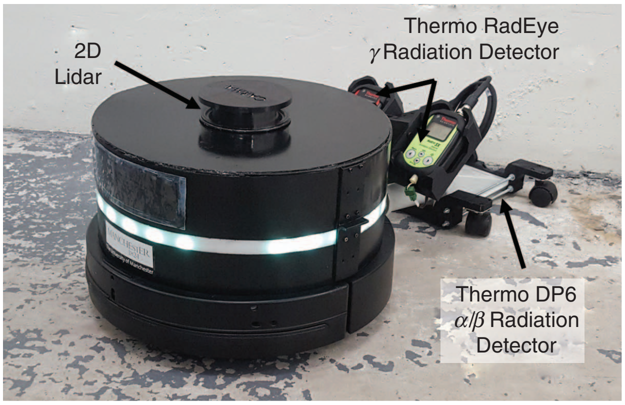

Figure 1. The CARMA platform.

Table 1. The CARMA robot specifications.

Parameter	CARMA
Base platform	TurtleBot 2
Dimensions including sensor tail ($l \times w \times h$)	$740\ \text{mm} \times 350\ \text{mm} \times 245\ \text{mm}$
Ground clearance	12 mm
Maximum speed	0.7 ms^{-1}
α/β sensors	One Thermo DP6
γ sensors	Two Thermo RadEyes
Navigational sensors	One 4-m lidar, one depth camera, three IR sensors
Battery life	3 h
Total cost	US$10,000

The operator interface for the robots is shown in Figure 2. The image was taken during a trial conducted at the University of Manchester's Dalton Cumbrian Facility using low-level thorium as an α source. The display shows a 2D map of the environment constructed using the lidar. Radiation data are superimposed on the map using visual markers. When the robot is tele-operated, the operator can avoid contaminated areas. A significant issue that we is address in this article is the risk that, if the robot moves through movable contamination, it may spread material through the environment. Hence, autonomous techniques were designed such that areas of contamination are mapped but not entered.

Radiation-avoidance navigation algorithms were developed for CARMA that allowed the robot to identify areas of radioactive contamination.

The vehicle contains no radiation shielding, and no hardened electronics are used. Although the environment will contain γ radiation (which can damage electronic components), only weak γ sources are likely to be in the areas where CARMA will initially be deployed, and these sources are unlikely to affect the robot's operation.

Autonomous Exploration, Localization, and Mapping

Autonomous exploration of an environment requires three components: a simultaneous localization and mapping (SLAM) algorithm (or only a localization algorithm if the map is pregenerated), an exploration algorithm for generating waypoints (points on the map that the robot must pass through), and a path-planning algorithm. All of these components represent well-established areas of research in robotics [12], and a number of reliable techniques can be used. The primary contribution of the work presented here is the development of an exploration algorithm that allows radiation maps to be constructed while ensuring the robot does not enter any areas of contamination.

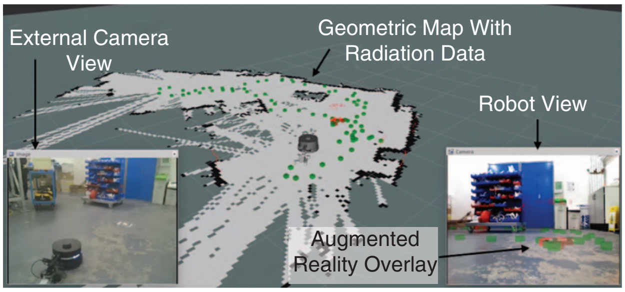

Figure 2. The CARMA operator interface, with an augmented reality overlay of the radiological data on the point-of-view camera. The values of the radiation data below a set threshold are shown in green, and the values above this are displayed in red.

Localization and Mapping

A number of SLAM algorithms are widely used on mobile robots. One of the most popular is FastSLAM, which combines both a particle filter approach with an extended Kalman filter (EKF). This technique fuses data from the odometry system and the 2D lidar to construct a map of the environment and localize the robot within it. It is widely used because of its higher efficiency and data accuracy compared to such methods as EKF-based SLAM algorithms [13]. The ROS Gmapping package is an implementation of FastSLAM and was implemented on CARMA.

In principle, if the environment is static, SLAM needs to be run only the first time the robot explores an area; after the map is generated, the robot is required only to localize itself within that map. This is also the case if the map is generated before the robot is deployed. In this scenario, a pure localization algorithm is needed. While a number of localization techniques are available, the Kullback-Leibler distance-sampling Monte Carlo approach was utilized in CARMA because it has proved sufficiently accurate in the environments where CARMA is expected to be deployed [14].

Exploration and Path Planning

The two scenarios considered for the deployment of the CARMA platform assume either that there is no prior knowledge of the environment or that the space has already been explored and a map generated. In the first case, waypoints need to be created to explore and map the area, while, in the second case, the robot needs to ensure complete coverage of the known map. Extensive research has been done in the autonomous exploration of environments using single and multiagent mobile robot systems, and three general methods have been developed to generate the exploration waypoints used when planning a suitable path: random, frontier, and human directed [15].

The most widely used approach for waypoint generation in an unexplored environment is the frontier technique [16]. In general, a map is built up by exploring the unknown areas of the environment. The exploration goal at any particular moment is the boundary between the known part of the environment and the unknown. This is because, if the robot is repositioned to this boundary, its sensors will have a vantage point over unknown areas of the environment; hence, the robot will be able to map those regions. The goal (the boundary between the unknown and known areas) should then be moved to allow for continued mapping of the environment. These boundaries between the known and unknown portions are called *frontiers* [17] and are explored based on a distance cost function. Different approaches can be taken to calculate this distance, such as the Euclidean distance [18] or the distance traveled avoiding local obstacles [17]. Because of its widespread use, frontier exploration was selected for the CARMA robot and implemented in ROS using the obstacle-avoidance cost function method [17].

When a map has been constructed, waypoints can be generated to ensure the total coverage of an area [19]. For CARMA, waypoints were overlaid onto the map in a grid, the dimensions of which can be specified by the user. The order in which waypoints are visited can be either random or systematic. During simulations, it was found that navigating to the waypoints in a randomized order provided superior coverage. However, for on-site deployment, the decision was made to adopt a systematic approach, as this gave the end users confidence that the robot was exploring the environment in a sensible manner, thus improving their confidence in the robotic technology.

The last component required for autonomous exploration is a path-planning algorithm. There are many well-documented approaches to path planning [20]. The A* method, which uses shortest-path and heuristic-based searching to select the best first path, is the most utilized approach to path planning within the robotics community. For the types of environments that CARMA is to be deployed into, it was felt to be the most appropriate technique to use. A* planning was implemented on CARMA using the Adaptive Monte-Calrlo Localization ROS package.

Radiation-Contamination Avoidance

To identify the location of α sources within the environment, the CARMA robot must physically maneuver to them because the required detection distance to the source is approximately 0.01 m. The robot should, however, avoid traveling over or through the contaminated areas, so that the vehicle itself does not become contaminated or spread radioactive materials elsewhere.

To minimize the risk of spreading radioactive matter within the environment, once a contamination area is detected, the robot was designed to stop its exploration and return to a previous location known to be safe. While the initial CARMA platform, as shown in Figure 1, must itself enter into a contaminated area before it is able to detect α-producing materials, it was anticipated that future designs of the vehicle would have a raised detector at the front of the vehicle that would allow α particles to be detected without the wheels of the vehicle having to enter into the contaminated area (the concern being that radioactive matter in the form of dust particles might adhere to the wheels and be spread to other locations).

If the contamination is spread across the entrance to a target area, the robot will not be able to enter to complete its inspection. In this scenario, it is envisaged that a human operator would make the decision as to whether the robot should cross over the contaminated area to continue the inspection, running the risk of further spreading the contamination, or whether the area has to be cleaned before the mission can continue.

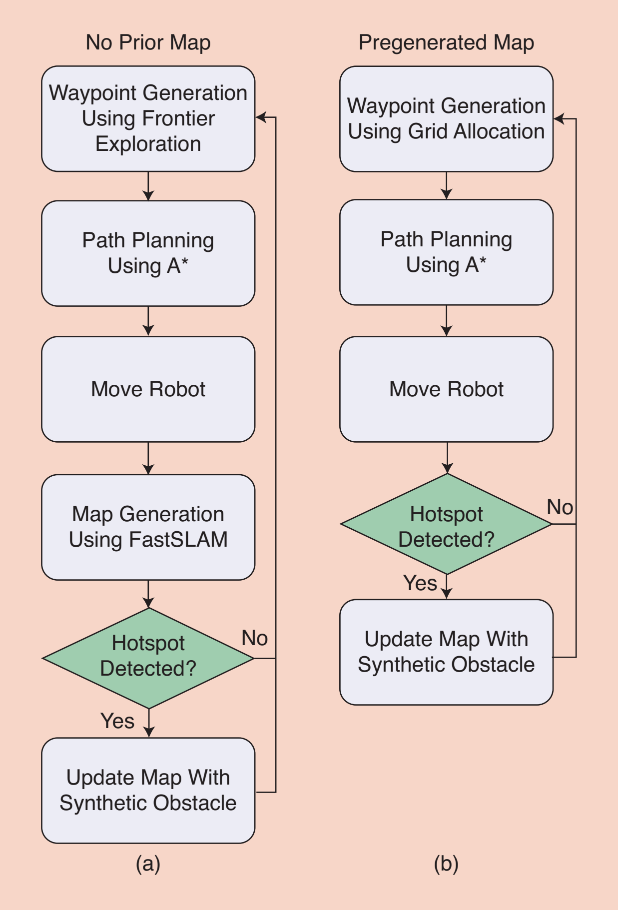

Figure 3. Flowcharts of CARMA's exploration routines: (a) with no prior knowledge of the environment and (b) with a pregenerated map given to the robot.

Once the vehicle returns to a safe location, the map is updated to identify the locality of the radiation source, and the robot is prevented from exploring that area. This functionality is achieved by directing the robot to explore the list of waypoints determined by the frontier exploration algorithm, while monitoring the dose rate CARMA is subjected to. If the dose rate exceeds a user-specified limit, the robot will stop and return to the previous safe waypoint. Once the machine has returned to a zone with a safe dose rate, the obstacle avoidance map is edited to include an exclusion zone.

Creating an exclusion zone is achieved by blocking out an area of the map, as if it were a physical obstacle. The A* path-planning algorithm uses the map to generate a global path and the local obstacles as seen by the sensing equipment (in this case, the lidar) to determine a suitable local path as well as to conduct localization. This allows for both localization errors and map/real-world disparity to be dealt with. Therefore, if a section of the map is blocked off, the path planner will avoid that area, thus keeping the robot out of the radiation zone.

Figure 3 summarizes CARMA's exploration routines in the form of flowcharts. Figure 3(a) assumes that the area is completely unknown, while Figure 3(b) assumes prior knowledge of the area and a pregenerated map.

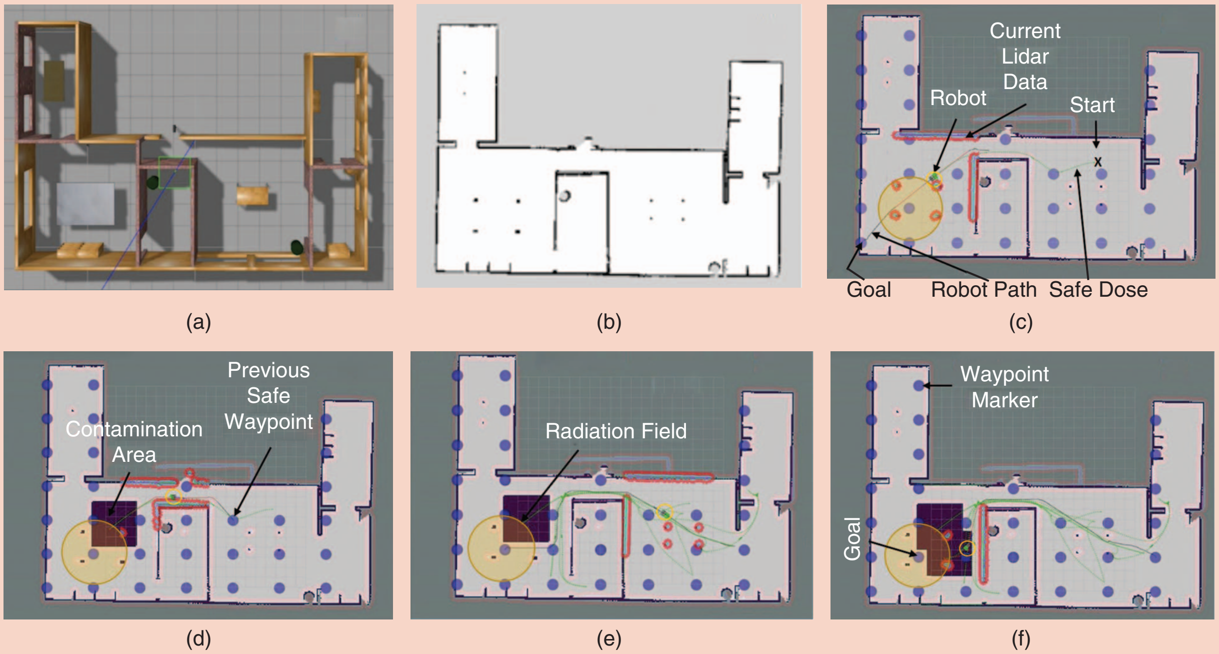

Figure 4. A depiction of CARMA's waypoint exploration of the simulated environment with radiation contamination avoidance. (a) The predefined "house environment." (b) A 2D map of the simulated environment. (c) The 2D obstacle map with the waypoint markers (blue) and simulated radiation field (orange). The robot's global path (as it navigates to the bottom left waypoint marker) is shown as a black/red line (black is the total global path, while red is the global path within the range of the robot's lidar), and the blue line is the robot's local path, which takes into account the real-time lidar data. The latter are shown in red, surrounding the obstacles on the 2D map. The green dots placed behind the robot indicate the safe dosage in that *xy* location of the 2D map. (d) The blocking of the exclusion zone in the 2D map. (e) A later point in the simulation where the robot has visited waypoints that are around the exclusion zone, showing that the path planner can create global paths to avoid it. (f) The robot's expansion of the exclusion zone.

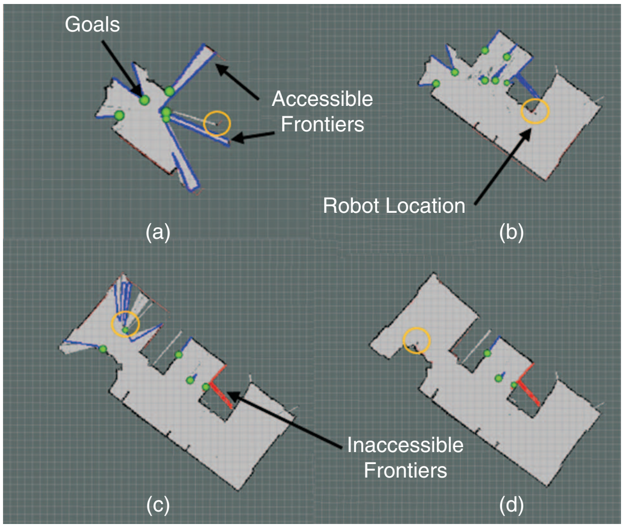

Figure 5. A frontier exploration of the office environment with FastSLAM map generation: the (a) initial scan, (b) generation of new frontiers, (c) identification of inaccessible frontiers, and (d) completed map. The green spheres represent the waypoints, the blue lines are the frontiers the robot is able to explore, and the red lines indicate the frontiers the robot cannot explore because it cannot get to a vantage point to observe them. The single red frontier is a result of a small gap in the walls making up the environment.

Simulation

To ensure that the proposed mapping and exploration techniques enabled the robot to function as required, the CARMA robot was simulated in Gazebo. Following this, laboratory testing was undertaken using a small-scale version of CARMA, based on a TurtleBot 3, that had similar characteristics to the actual CARMA robot. Simulations were conducted in the predefined house environment, shown in Figure 4(a). This environment was considered to be similar to those that the CARMA robot would be deployed into in the nuclear industry and requires a nontrivial path to travel between waypoints. A premade 2D map of the simulated environment is illustrated in Figure 4(b). Using this simulation environment, it was also possible for the user to insert a synthetic radiation contamination area that the robot would need to detect, map, and avoid.

The simulated waypoint exploration based on the pregenerated map algorithm from Figure 3 is presented in Figure 4. Figure 4(c) shows the 2D obstacle map. The robot is depicted navigating to the bottom-left waypoint marker. The figure shows the robot as it enters an area where the maximum safe radiation dose threshold is just exceeded. The waypoint the robot was initially navigating to is canceled, and the robot navigates back to the previous waypoint known to be safe. The exclusion zone in the 2D map is then blocked, as shown in Figure 4(d), so the global planner will no longer direct the robot to that location.

Figure 4(e) shows a later point in the simulation, where the robot has visited waypoints that are around the exclusion zone, showing that the path planner can create global paths that can avoid it. In Figure 4(f), the robot has expanded the exclusion zone when it tries to visit another waypoint in the radiation field. As before, the robot returns to a previous safe waypoint before continuing with the navigation. Over time, the robot will block out all of the area surrounding the radiation field.

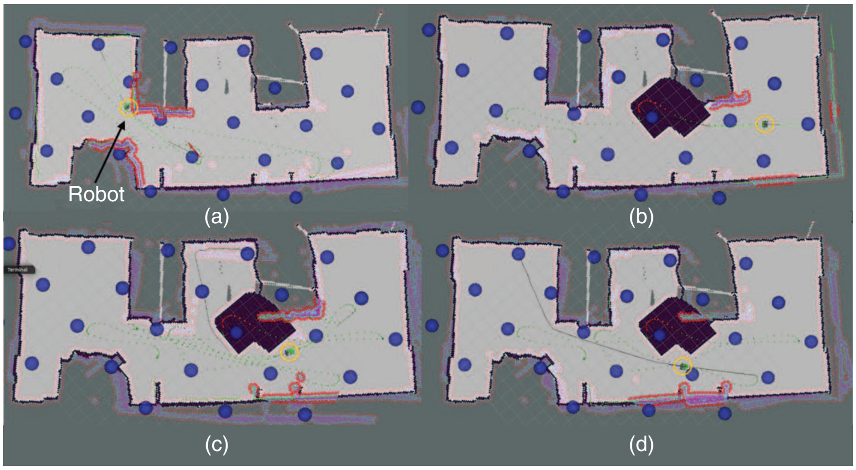

Figure 6. The (a) waypoint generation in a pregenerated map, (b) addition of an exclusion zone for the simulated source, (c) path planning to avoid the exclusion zone, and (d) final paths for full exploration.

Physical Evaluation

A set of real-world experiments was conducted in which the algorithms were implemented on the simplified TurtleBot 3-based CARMA, which was deployed in an E-shaped office environment. The first set of tests was to validate that the SLAM and exploration algorithms operated as expected. Figure 5 shows the exploration of the environment using FastSLAM and frontier search. This experiment was concerned only with map generation, so no synthetic contamination areas were used.

Once the 2D obstacle map was generated, a second experiment was conducted that directed the robot to map the dose rate of the environment. A synthetic hot spot was generated, and the robot was tasked with finding and avoiding this radiation source. As shown in Figure 6, the robot was successfully able to identify the location of the hot spot and avoid navigating through the exclusion zone surrounding it.

Real-World Deployments

As a final proof of concept, the CARMA robot was successfully deployed twice into operational facilities within the Thermal Oxide Reprocessing Plant (THORP) on the Sellafield site. THORP takes spent fuel and separates the uranium and plutonium in preparation for future safe storage.

The purpose of the deployments was to gain confidence that a robot-mounted radiation sensor could detect a contamination source autonomously. Both deployments took place in a facility where there was a known α contamination source embedded in the floor. This contamination source was well understood and presented no physical danger to humans or to the robot. Because of the nature of the contamination, there was no risk of it being transferred to the robot, and, because of time restrictions during the real-world deployments and the inability to spread the contamination, it was decided not to implement the hot-spot avoidance algorithm and to focus only on generating the radiation map.

The area to be inspected had a flat surface, with industrial equipment and pipework around the edges, as pictured in Figure 7. The inspections took approximately 30 min to complete. Figure 8 shows the outputs from one

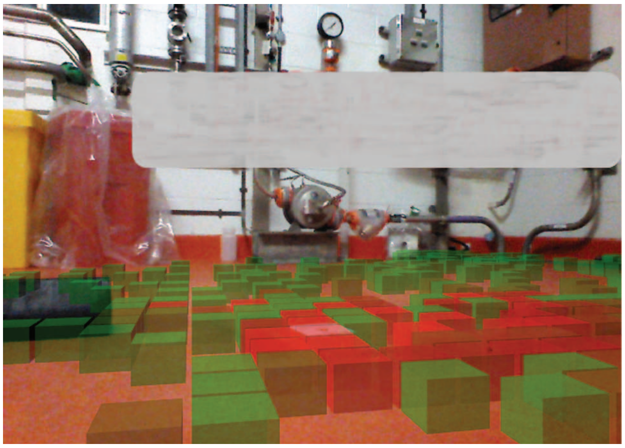

Figure 7. An augmented reality camera perspective for operator control and observation. The image has been modified to remove radiological threshold data. Areas of no contamination are represented in green, and the contamination hot spot is shown in red.

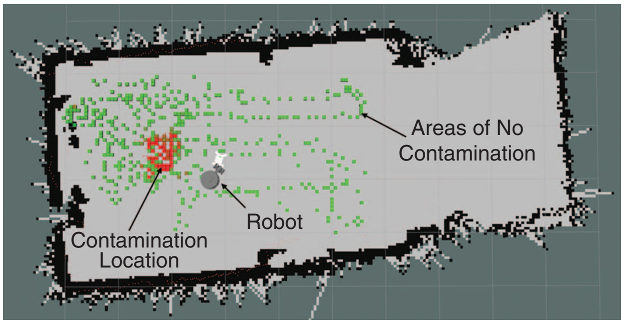

Figure 8. A radiological map generated by CARMA at the THORP facility. Areas of no contamination are represented in green, and the contamination hot spot is shown in red.

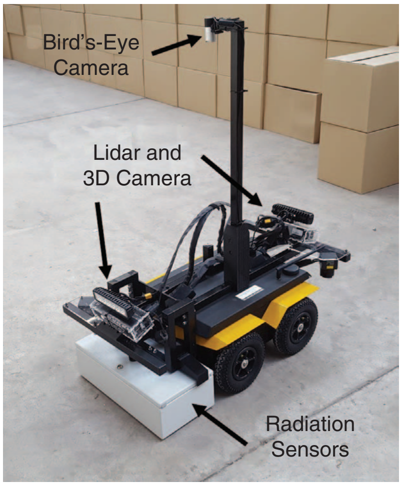

Figure 9. The CARMA 2 platform, currently under development.

Table 2. The CARMA 2 robot specifications.

Parameter	CARMA 2
Base robot	Clearpath Jackal
Dimensions including sensors and cameras ($l \times w \times h$)	830 mm × 440 mm × 1,030 mm
Ground clearance	65 mm
Maximum speed	$2\ \mathrm{ms}^{-1}$
α/β sensors	Two Thermo DP6s
γ sensors	Three Thermo RadEyes
Navigational sensors	Two 20-m lidars, two 3D cameras, one webcam
Battery life	3–4 h
Total cost	US$35,000

of the real-world deployments, which highlights that the robot was able to successfully construct a geometric and radiological map of the area. The location of the contamination source on the map correlated to its correct physical location in the real world. Quantification of the accuracy of the α source location was not possible during the deployment. For these experiments, only α radiation was of interest, and, consequently, no β or γ measurements were recorded.

The CARMA robot can be maneuvered in both teleoperational and autonomous mode. Figure 7 shows the augmented reality view from a camera on the front of the robot, which can be used for tele-operation or operator observation.

Future Development

The CARMA robot was developed to operate in indoor environments free from clutter. While there are many areas where it could be deployed, a more robust platform is required for outdoor use or for areas where there are small obstacles, such as cables or pipework.

A second-generation CARMA robot, CARMA 2, is shown in Figure 9. CARMA 2 is able to survey both indoor and outdoor environments and maneuver in areas with uneven terrain and clutter. The CARMA 2 specifications are shown in Table 2. The robot utilizes the Clearpath Jackal robot as its base platform and has been equipped with two Thermo Fisher Scientific DP6 sensors on a height-adjustable rig and three personal dosimeters. Its navigation suite consists of two 20-m lidars, two 3D cameras (Orbbec Astra), and a camera that provides a bird's-eye view for operator observation.

The next stage of autonomy development will be to implement the radiation contamination avoidance algorithms. One of the primary challenges to overcome is that the simulations assume that the radiation sensors have a 360° view around the robot and that the robot is holonomic. CARMA 2 is a nonholonomic platform, with the sensor package mounted at the front of the robot; consequently, further development is required.

There are no plans to develop the CARMA 2 robot to explore high γ-dose environments. Experience gained from other groups deploying robots into high γ-dose environments at Fukushima Daiichi has shown that they are likely to fail, which has proven to be quite costly. The focus of future CARMA deployments will be in areas that people could access in environmental suits or where they perform repetitive monitoring operations.

The CARMA 2 robot is in the process of being commercialized, with further laboratory testing and on-site deployments planned. The long-term vision is to have a fleet of CARMA robots continuously monitoring facilities like the Sellafield sites.

Conclusions

This article presented the CARMA robot, an autonomous platform for conducting radiological monitoring in nuclear facilities. The proof-of-concept robot was successfully deployed in a radioactive facility on the Sellafield site, where it was able to autonomously locate a known α source embedded in the floor and generate a geometric and radiometric map of the area. This was the first time an autonomous inspection vehicle had been deployed at the Sellafield site, which represents a major milestone in making the deployment of autonomous robotic systems commonplace in the nuclear industry.

Radiation-avoidance navigation algorithms were developed for CARMA that allowed the robot to identify areas of radioactive contamination while minimizing the risk of entering the area and potentially transporting radioactive materials to other locations within the environment.

A more rugged version of the CARMA platform (CARMA 2) is now in development. CARMA 2 is being designed such that it will be able to operate in a larger range of both indoor and outdoor nuclear environments or scenarios.

Acknowledgments

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References

[1] "Nuclear technology review 2017," Int. Atomic Energy Agency, Vienna, Austria, GC(61)/INF/4, 2017. [Online]. Available: https://www-legacy.iaea.org/About/Policy/GC/GC61/GC61InfDocuments/English/gc61inf-4_en.pdf

[2] K. Ooi, K. Yasutomo, and Z. Suzuki, "Nuclear facility radiation monitoring system," Fuji Electric Co., Shinagawa, Japan, Tech. Rep. 53, 2007.

[3] J. M. Shuler, *Understanding Radiation Science: Basic Nuclear and Health Physics*. Irvine, CA: Universal Publishers, 2006.

[4] Y. Sato *et al.*, "Radiation imaging using a compact Compton camera inside the Fukushima Daiichi Nuclear Power Station building," *J. Nucl. Sci. Technol.*, vol. 55, no. 9, pp. 965–970, 2018. doi: 10.1080/00223131.2018.1473171.

[5] P. Martin *et al.*, "3D unmanned aerial vehicle radiation mapping for assessing contaminant distribution and mobility," *Int. J. Appl. Earth Observ. Geoinform.*, vol. 52, pp. 12– 19, Oct. 2016. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0303243416300733

[6] S. Kawatsuma, R. Mimura, and H. Asama, "Unitization for portability of emergency response surveillance robot system: Experiences and lessons learned from the deployment of the JAEA-3 emergency response robot at the Fukushima Daiichi Nuclear Power Plants," *ROBOMECH J.*, vol. 4, no. 1, pp. 6, Feb. 2017. doi: 10.1186/s40648-017-0073-7.

[7] K. Nagatani *et al.*, "Emergency response to the nuclear accident at the Fukushima Daiichi Nuclear Power Plants using mobile rescue robots," *J. Field Robot.*, vol. 30, no. 1, pp. 44–63, Jan./Feb. 2013. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/rob.21439

[8] C. Ducros *et al.*, "RICA: A tracked robot for sampling and radiological characterization in the nuclear field," *J. Field Robot.*, vol. 34, no. 3, pp. 583–599, May 2017. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/rob.21650

[9] M. Zavala, "Autonomous detection and characterization of nuclear materials using co-robots," M.S. thesis, Georgia Inst. Technol., Atlanta, 2016.

[10] F. Zhao, Y. Ma, and Y. Sun, "Application and standardization trend of maintenance and inspection robot (MIR) in nuclear power station," in *Proc. 3rd International Symposium on Mechatronics and Industrial Informatics* (*DEStech Transactions on Engineering and Technology Research*), 2017.

[11] M. Nancekievill, "The radiation tolerance and development of robotic platforms for nuclear decommissioning," Ph.D. dissertation, Univ. Manchester, U.K., 2018.

[12] C. Cadena *et al.*, "Past, present, and future of simultaneous localization and mapping: Toward the robust-perception age," *IEEE Trans. Robot.*, vol. 32, no. 6, pp. 1309–1332, Dec. 2016.

[13] M. Montemerlo, S. Thrun, D. Koller, and B. Wegbreit, "FastSLAM: A factored solution to the simultaneous localization and mapping problem," in *Proc. Association for the Advancement of Artificial Intelligence Nat. Conf. Artificial Intelligence*, 2002, pp. 593–598.

[14] D. Fox, "Adapting the sample size in particle filters through KLD-sampling," *Int. J. Robot. Res.*, vol. 22, no. 12, pp. 985–1003, 2003. doi: 10.1177/0278364903022012001.

[15] S. Sharma and R. Tiwari, "A survey on multi robots area exploration techniques and algorithms," in *Proc. Int. Conf. Computational Techniques Information and Communication Technologies*, Mar. 2016, pp. 151–158.

[16] M. Keidar and G. A. Kaminka, "Efficient frontier detection for robot exploration," *Int. J. Robot. Res.*, vol. 33, no. 2, pp. 215–236, 2014. doi: 10.1177/0278364913494911.

[17] J. Hörner, "Map-merging for multi-robot system," 2016. [Online]. Available: https://is.cuni.cz/webapps/zzp/detail/174125/

[18] T. Andre, D. Neuhold, and C. Bettstetter, "Coordinated multi-robot exploration: Out of the box packages for ROS," in *Proc. IEEE Global Communications Conf. Workshops*, 2014, pp. 1457–1462.

[19] H. Choset, "Coverage for robotics: A survey of recent results," *Ann. Mathematics Artificial Intell.*, vol. 31, no. 1, pp. 113–126, Oct. 2001. doi: 10.1023/A:1016639210559.

[20] A. Koubaa *et al.*, *Robot Path Planning and Cooperation*. Berlin: Springer-Verlag, 2018.

Benjamin Bird, School of Electrical and Electronic Engineering, University of Manchester, U.K. Email: benjamin.bird@manchester.ac.uk.

Arron Griffiths, School of Electrical and Electronic Engineering, University of Manchester, U.K. Email: arron.griffiths@manchester.ac.uk.

Horatio Martin, School of Electrical and Electronic Engineering, University of Manchester, U.K. Email: horatio.martin@manchester.ac.uk.

Eduardo Codres, School of Electrical and Electronic Engineering, University of Manchester, U.K. Email: eduardo.codres@manchester.ac.uk.

Jennifer Jones, School of Electrical and Electronic Engineering, University of Manchester, U.K. Email: jennifer.jones@manchester.ac.uk.

Alexandru Stancu, School of Electrical and Electronic Engineering, University of Manchester, U.K. Email: alexandru.stancu@manchester.ac.uk.

Barry Lennox, School of Electrical and Electronic Engineering, University of Manchester, U.K. Email: barry.lennox@manchester.ac.uk.

Simon Watson, School of Electrical and Electronic Engineering, University of Manchester, U.K. Email: simon.watson@manchester.ac.uk.

Xavier Poteau, Sellafield Ltd., U.K. Email: xavier.poteau@sellafieldsites.com.