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Vega—A small, low cost, ground robot for nuclear decommissioning

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Abstract

This paper presents the Vega robot, which is a small, low cost, potentially disposable ground robot designed for nuclear decommissioning. Vega has been developed specifically to support characterization and inspection operations, such as 2D and 3D mapping, radiation scans and sample retrieval. The design and construction methodology that was followed to develop the robot is described and its capabilities detailed. Vega was designed to provide flexibility, both in software and hardware, is controlled via tele-operation, although it can be extended to semi and full autonomy, and can be used in either tethered or untethered configurations. A version of the tethered robot was designed for extreme radiation tolerance, utilizing relay electronics and removing active electronic systems. Vega can be outfitted with a multitude of sensors and actuators, including gamma spectrometers, alpha/beta radiation sensors, LiDARs and robotic arms. To demonstrate its flexibility, a 5 degree-of-freedom manipulator has been successfully integrated onto Vega, facilitating deployments where handling is required. To assess the tolerance of Vega to the levels of ionizing radiation that may be found in decommissioning environments, its individual components were irradiated, allowing estimates to be made of the length of time Vega would be able to continue to operate in nuclear environments. Vega has been successfully deployed in an active environment at the Dounreay nuclear site in the UK, deployed in nonactive environments at the Atomic Weapons Establishment, and demonstrated to many other organizations in the UK nuclear industry including Sellafield Ltd, with the goal of moving to active deployments in the future.

KEYWORDS

3D robotic mapping, field robotics, industrial robotics, vehicle robot

1 | INTRODUCTION

The use of robotic systems in unstructured environments, such as accident response, search and rescue and in domestic environments is increasing rapidly. In 2008, Murphy et al. highlighted how robotic systems were beginning to be used in rescue missions at sites including the World Trade Centre and following hurricane Katrina (Murphy et al., 2008), but at that time many challenges remained before the full benefits of these systems could be realized. The limitations of the robotic systems, available at the time, were further highlighted in the immediate aftermath of the Fukushima Daiichi Nuclear Power Plant accident in 2011. This incident clearly demonstrated the importance of robotic systems, but it also highlighted the limited availability of robotic systems that had been designed and tested for use in such environments and in particular situations involving radioactive materials (Nagatani et al., 2013). Ten years after the Fukushima Daiichi incident there have been many advances in mobile robotics, with commercial systems now available for use on land, air, and in water. However, robotic systems remain underutilized in the nuclear industry and hence their potential benefits are not yet being realized. Whilst the requirements for a robotic system may, generally, be quite similar for a robot designed to search for survivors following a natural disaster and a robot designed to explore and inspect a nuclear facility, there are also many differences and these differences often mean that robotic systems designed for other applications are not well suited to support nuclear operations.

The nuclear industry is responsible for many legacy facilities that are in the process of being decommissioned. These facilities range from research and development laboratories built in the 1940s, to more recent plants, which have come to the end of their design life (Lee et al., 2020; West et al., 2019; Zhang et al., 2020). Nuclear decommissioning is an expensive and time consuming process, mainly due to the hazardous nature of the work (Sato et al., 2019), which is compounded by uncertainties in the nuclear materials that may be present and the integrity and layout of facilities (Bandala et al., 2019). The scale of the problem is enormous with the UK's Nuclear Decommissioning Authority estimating that there is approximately 310,000 tonnes of intermediate level waste that needs to be disposed of in the UK alone and that decommissioning the UK's legacy facilities will take 120 years and cost between £99Bn and £232Bn (Nuclear Decommissioning Authority, 2019).

To address the uncertainty with regard to the layout of facilities and the precise nature of radioactive materials that may be present, the initial stage in many decommissioning projects involves surveying the facility and characterizing the materials within it. This might involve using laser range finders and cameras, for example, to identify the geometry of a facility and sensors, such as radiation detectors, to measure radiation dose rate and identify properties of the materials that are present. These activities would traditionally be completed manually by operations staff, but even in situations where human access is permitted, the nature of the environment means that there are risks associated with this and the costs can be excessive (Cooke et al., 2019). There is therefore growing interest in the use of robotic systems to support the characterization of nuclear environments.

A significant challenge when utilizing robotic systems in the nuclear industry is the potential for them to be contaminated, with radioactive materials that may be mobile within the environment that the robot is placed. This can mean that it is not possible to retrieve the robotic system once it has been deployed (Gianni, 2019; Tsitsimpelis et al., 2019), which introduces additional costs, as well as increasing the amount of waste that needs to be disposed of. While it is possible to clean a robot of contamination, unless all its surfaces are smooth and there are no areas, such as the tread of a tyre or the head of a bolt, where radioactive materials may accumulate, then the risk imposed on the person responsible for cleaning the robot will typically be considered to be too high to justify.

The Vega robot, described in this paper, has been designed specifically to be low cost, such that if necessary it does not need to be retrieved once it has been used and therefore has been designed to reduce but not eliminate contamination traps on the vehicle. It has also been designed such that it is safe for both the operators to handle, and the environment in which it will be deployed. Of particular significance is that experience from this and other nuclear robotics projects have highlighted that CE marking is of fundamental importance for any commercially deployed robot and as a consequence CE marking was considered throughout the design stage. The CE mark is a form of certification that indicates conformity to a number of European regulations concerning health and safety as well as environmental protection (Hanson, 2005).

This paper seeks to share the lessons learned in designing Vega for nuclear decommissioning, and describes many of the compromises and constraints that were made to satisfy health and safety requirements.

2 | LITERATURE REVIEW

The nuclear industry, like many sectors of heavy industry, has an increasing interest in the use of robotics for day to day tasks. Of particular interest to this study is the exploration and decommissioning of both legacy facilities and facilities which have been the subject of nuclear accidents. A common theme is that the robots traditionally produced for nuclear applications tend to be large, heavy, and cumbersome. There are a number of reasons for this, but a major factor has been the slow adoption in the nuclear industry of the recent advances that have been made in sensors, actuators and microcontrollers, and a continued reliance on relatively old technologies. As a consequence, the robotic systems used to date in the nuclear industry have been very expensive in terms of development cost and the sacrificial cost, should they need to be abandoned.

There are a number of examples of robotic systems that have been successfully developed for the nuclear industry. For example, Voyles et al. (2017) took a novel approach to ground robot locomotion, presenting a collaborative system in the form of MOTHERSHIP, an articulated and segmented snake-like robot, encased 360 degrees in continuous tracks, enabling it to traverse a wide variety of obstacles. The tracks were driven by a single DC motor and clutch system that transferred torque to a specific track. A segmented and articulated snake-like robot, significantly smaller than the MOTHERSHIP, and also designed and built by Voyles et al., was mounted at the front of MOTHERSHIP to provide an end effector. Voyles et al. highlighted that the reason for the use of the snake-like robot was that it was better able to perform the highly articulated movement that was necessary to complete inspection tasks in the confined spaces the robot was to be deployed in, when compared with other manipulator designs. In contrast to this approach, West et al. (2019), Ducros et al. (2017), and Kawatsuma et al. (2017) presented more conventional, differential drive robots with designs chosen for their simplicity and robustness, both in terms of design and in the robot's ability to tackle challenging terrain. The three designs were however relatively large in both size and mass, Ducros et al.'s design having dimensions of 570 × 420 × 330 mm (L W H) and a mass of 80 kg, West et al.'s design had dimensions of 990 × 670 × 390 mm, a mass of 50 kg, and 700 × 700 mm, 70 kg in Kawatsuma et al.'s case. A design in the middle ground in terms of complexity and ability was presented by Guzman et al. (2016), and named Rescuer, which was a large articulated continuous track robot, capable of being outfitted with multiple locomotion configurations. This included the use of four separate continuous tracks that could be rotated independently depending on terrain, or alternatively four independent wheels could be used, or a combination of fixed continuous tracks, articulated tracks and wheels. Rescuer had a mass of 105 kg, and while its dimensions were not provided, its mass suggests that it must be relatively large.

A particular challenge with the deployment of robotic systems into nuclear environments is that of communications, from operator to robot for command and control, and from robot to operator for telemetry. The reason this is a challenge is that nuclear environments typically contain thick, dense concrete structures and walls, to shield against radiological hazards. Furthermore, the environments are typically cluttered, making the use of tether systems problematic due to the potential to tangle and snag (West et al., 2019). Several examples of Ethernet based tether systems are highlighted in the work of Ducros et al. (2017). Voyles et al. (2017) relied on a WiFi connection to a base station for telemetry and control, and Guzman et al. used a combination of WiFi, low bandwidth 900 MHz radio (120 kbps, up to 50 km), a cellular 3G modem and Ethernet over fiber-optic cable. However, the 3G link was proven to be unsuitable due to the lack of connectivity in the target environment. Guzman et al.'s robot was outfitted with large batteries, and the Ethernet telemetry system was deployed over fiber-optic, which meant that theoretically a 30 km tether could be used. Kawatsuma et al. (2017), communicated between the robot and base station via a 50 m tether system, which was deemed to be too short, as the operators were in some cases exposed to radiation during the robot's use. Power was provided to the robot via a tether system that used a bank of lead acid batteries to save mass and increase ease of transportation, when compared to the petrol generator system the robot was initially designed to use. West et al. (2019), proposed a tether management system to prevent their tether from tangling in the robot's drive mechanism and snagging in the environment, which was stated to be a significant risk in their work, and could potentially cause the robot to become stuck and have to be abandoned.

Decontamination of a robot that has been in an active nuclear environment is a key aspect of deployment. Once deployed and exposed to mobile radioactive contamination, the robot cannot be extracted from the environment without creating a health hazard to the operator, or risk spreading contamination from the environment. The RICA robot (Ducros et al., 2017) was designed to be decontaminated using detergent and a high pressure water spray, as such it was water resistant up to a pressure of 2 barg. Standard decommissioning procedure for the RICA necessitated that the tracks were removed and treated as low level waste.

Depending on the environmental use case, radiation tolerance may also be a factor that needs to be taken into account. A major concern that limits the deployment of robots into decommissioning environments is that there is a danger that electronic or mechanical failure, in particular caused by the effects of gamma radiation, may cause them to be abandoned, potentially blocking critical pathways. In nuclear disaster response situations, such as Fukushima Daiichi, it can be essential that robots are deployed despite this risk (Zhang et al., 2020). Ducros et al. performed radiation tolerance testing, and found that power supply components were by far the most susceptible and had on average a tolerance of up to 210 Gray (Gy) total ionizing dose (TID) at a dose rate of 1.9 Gyh^{-1}. Other electronic components were found to be much more tolerant, surviving TIDs of 2200 Gy. Nancekievill et al. (2016) found similar results in their radiation tolerance testing of CoTS electronic components.

As a consequence of the high-likelihood of not being able to retrieve a robot once it has been deployed, the cost of the robot itself should be considered in any operation. Voyles et al. estimated the cost of the sacrificial part of their system to be approximately $75 k, and West et al. estimated the approximate cost of their system to be £30 k for the chassis and £36 k for the mounted manipulator payload.

While the reviewed work highlighted a number of robotic systems that have been deployed in nuclear facilities, their size, mass and cost means that the deployment of robotic systems in the nuclear industry remains an infrequent activity. Whilst consideration was taken in some cases to ensure that the robots could be decontaminated (wheels/tracks removed and disposed of, chassis washed with detergent and pressure washer Guzman et al., 2016; Kawatsuma et al., 2017), this still required operators to physically clean the robot, which introduces risk, and this necessity had to be taken into account during the design phase (such as ensuring the robot was water tight). All of the reviewed works featured some kind of robotic manipulator, however, in the specific applications that were being addressed there was no evidence presented that showed a requirement that the payload needed to be 5 kg or more (with the exception of West et al's work; West et al., 2019), with many tasks in radioactive environments, such as gathering small samples or taking surface swab samples for later chemical analysis, typically possible with a much lower payload capacity.

Several methods for locomotion were presented, a differential continuous track system was indicated to be the most robust in terms of design and would be able to cope with a wide variety of obstacles. It was also the simplest design to implement. A wheeled locomotion system presented the simplest, most robust and typically the most energy efficient option, however it was limited in the complexity of the terrain it could navigate. It was felt that a hybrid system with tracks and wheels, would not provide improved obstacle navigation over a tracked system and would be more complex. An articulated track system, whilst being superior at obstacle navigation, would have increased complexity compared to other locomotion systems, and would also have a higher number of failure points, would typically be more expensive and would be time consuming to design, making such a system undesirable.

For a more comprehensive review of the state of robotics within the nuclear decommissioning industry, from the mid 1970s through to 2019, the reader is directed to the work of Tsitsimpelis et al. (2019), which provides a comprehensive overview of the use of ground-based robots in the nuclear industry. Unfortunately, none of the robotic systems presented above or elsewhere have led to the widespread adoption of robotic systems for characterization of nuclear facilities. The aim of the work described in this article was therefore to deliver a low-cost system that could be mass produced, allowing it to be used as widely and as frequently as possible in the nuclear industry.

3 | DESIGN SPECIFICATION

The literature review (Section 2) highlighted several shortcomings in the state of the art of robotics for nuclear decommissioning and disaster response. Therefore a specification was established that would allow a robot to function in a relatively generic nuclear decommissioning environment, whilst addressing the shortcomings of previously deployed robots. The nuclear industry contains a wide variety of scenarios where robotic solutions would add value. These include highly complex scenarios in accident situations, the automated sorting and segregation of waste materials and materials characterization in facilities such as legacy laboratories and process plants. The target deployment for the robot developed in this study was for it to support the characterization of relatively generic environments on legacy nuclear sites, completing tasks such as generating radiation maps of facilities, identifying materials within an environment, and when necessary collecting small samples and taking swabs for subsequent laboratory analysis. These activities help gain a better understanding of the conditions and materials within an environment, aiding in the development of decommissioning plans. To meet this target deployment, the specifications for the robot, which were identified following comprehensive discussions with engineers working for several UK nuclear end-users are detailed below, together for the reasoning for these specifications:

1. Mass of less than 10 kg (excluding radiometric detectors and other specialist sensors). This enables the robot to be transported and manoeuvred into an initial deployment position by a single operator without special handling considerations.
2. Dimensions, length, width and height of less than 400 × 400 × 300 mm, respectively (excluding radiometric detectors). This reduces the risk of the robot becoming an obstacle in the event of failure and allows deployment through limited sized access ports.
3. Differential drive continuous track locomotion, capable of traversing obstacles of up to 45 mm in height. This allows the robot to negotiate a wide variety of complex terrains that may contain small amounts of rubble and steps.
4. Built in safety cut off: prevents a runaway robot scenario.
5. Modular communication ability, allowing for both wireless and tethered (up to 100 m) use. This provides the robot with the flexibility to be deployed indefinitely, have wireless free communications and increased mobility afforded by a tether free system.
6. Modular sensor payload capability, allowing for a wide range of radiometric and environmental sensors to be integrated. This accommodates the varying requirements of different organizations and scenarios, who utilize a range of sensors.
7. Operating life of at least 2 h, with a life of 8 h strongly desired to allow the robot to operate for a full shift rotation. This provides sufficient time for relatively large surveys and inspections to be carried out.
8. Battery system that can be removed and replaced by operator with limited dexterity. This allows prolonged operating life and battery changes to be made by operators wearing one or more pair of thick gloves.
9. Bill of Materials (BoM) cost of less than £2000 (excluding radiometric detectors and other specialists sensors). This raises the potential of the robot to be disposable if necessary.
10. Utilize as much CoTS hardware as possible, with pre-existing CE certification, to allow for a streamlined CE marking process of the system as a whole.
11. Have the facility to mount and control a small robotic manipulator arm. This provides the capability to collect samples or takes swabs for laboratory analysis.
12. Capable of exploration and mapping, in a tele-operated capacity, with the potential in the future to extend to autonomous operation. This allows characterization maps to be generated of facilities.
13. Be capable of operating in a wide variety of radioactive environments, culminating in a minimum operational lifetime (due to radiation damage) of 8 h, in a high dosage environment. As an example, Vega should be capable of inspecting a hot spot in a pressurized water reactor, where the dose rate may be as high as 2 Gy/h, giving a TID of 16 Gy (DiBuono et al., 2020). This gives flexibility in the types of environment the robot can be deployed into.
14. Designed with commercial production in mind. This allows the robot to be commercialized and produced in quantity.

4 | THE VEGA ROBOT

Vega, shown in Figure 1 is the robot that was designed to meet the specifications discussed in Section 3. Vega is capable of operating indefinitely in tethered mode, and for relatively long periods of time in battery mode (see Section 5.1, for further details), allowing for lengthy deployments. The total mass of Vega, in the configuration shown in Figure 1 is 5.5 kg. Both 3D and 2D SLAM are provided by the on-board LiDAR (Slamtec RPLiDAR A1) and 3D camera (Intel RealSense D435i), using relatively standard techniques such as RTABmap (Labbé & Michaud, 2019), Gmapping (Balasuriya et al., 2016), and Cartographer (Nüchter et al., 2017). The 3D SLAM system has been tested successfully at AWE, and was able to provide sub 5 cm accuracy (successful loop closure) over a trajectory of 150 m in a cluttered, indoor environment. A first person view (FPV) stream is also provided to allow tele-operation of the robot. Vega is capable of fully autonomous exploration (using frontiers based exploration, Horner, 2016, which has been demonstrated in previous work—Bird et al., 2018). While full autonomy was not part of the original specifications, the nuclear industry is keen to explore its potential and so the capability was included for demonstration purposes only. However, it is recognized that in the short-term there is a general desire for robotic solutions to be tele-operated (Bandala et al., 2019; West et al., 2019). Security restrictions vary across different nuclear facilities and for deployments on certain sites it will be necessary for the base station computer (which is used to operate Vega) to be a site owned machine. Therefore the tele-operation system was designed to use a minimum number of additional pieces of equipment.

Online 3D point clouds are produced by RTABmap (Labbé & Michaud, 2019), giving the operator a coarse representation of the environment to help avoid obstacles, and a dense, detailed point cloud can be computed in post processing using the FPV camera's video stream, and structure from motion software. RTABmap was chosen due to it being mature, actively maintained, its ability to work with a wide range of sensory equipment and its loop closure and memory management algorithms allowing for lengthy deployments in an environment without the need for large amounts of memory. The real-time, coarse point cloud generated by RTABmap can be saved at the discretion of the operator and inspected to determine measurements of the environment, such as structure dimensions or pathway width to determine if Vega is capable of proceeding in that direction. In tests completed during development, the coarse point clouds were found to have an accuracy of up to ±5 mm, with ±8 mm being typical. This accuracy was primarily due to parallax errors in point cloud measurement, as well as sensor error.

Vega can traverse relatively complex terrain, and is able to manoeuvre itself over obstacles with up to a 45 mm lip. Vega has a maximum tested payload of 5 kg and can move at up to 0.9 ms^{-1}. The available torque in the drive motors (4.1 Nm at 12 V) would allow for more substantial payload, however this has not been tested.

5 | SYSTEM OVERVIEW

Vega is outfitted with a 3D camera (Intel RealSense 435i), 360 degree LiDAR (Slamtec RPLiDAR A1), and has external I/O ports (Ethernet, USB 2.0/3.0, HDMI, 12v/5v) which enable bespoke sensors to be fitted to the robot with relative ease. For example, for a demonstration deployment for the AWE, the CC-RIAS from Imitec was installed on to the robot. Further information on integrated sensor payloads is provided in Section 5.4.

5.1 | Telemetry and power systems

Initially, Ethernet over Power technology, which is related to the Power over Ethernet (PoE) that is commonly found in domestic WiFi extenders was considered. In such a system, data would be sent using

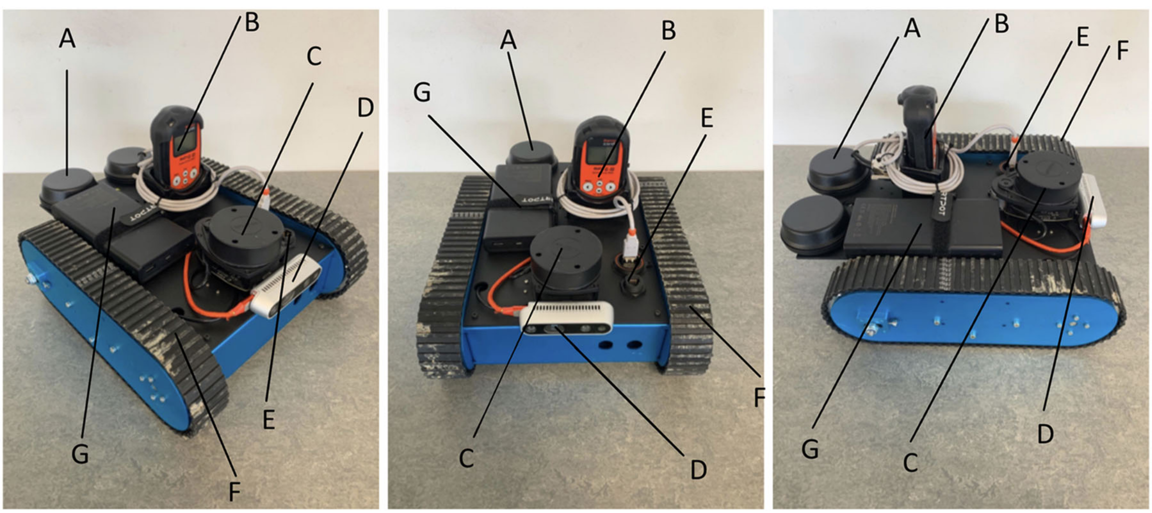

FIGURE 1 Vega robot, in wireless form with common sensor configuration. Component parts shown—A, WiFi Antenna; B, ThermoFisher RadEye G10 gamma sensor; C, LiDAR; D, 3D camera; E, payload IO port; F, track system; and G, battery [Color figure can be viewed at wileyonlinelibrary.com]

a 100 m, 48 V DC, twisted pair wire system. The reason for using 48 V is that anything above 50 V would require additional certification under the CE marking directive of electrical equipment (Hanson, 2005), and present additional hazards, which was to be avoided if possible. Unfortunately, 100 m of unshielded twisted pair caused significant packet loss in the telemetry, limiting the video feed to approximately 0.5 frames per second (FPS). Reducing the tether to 60 m was shown in experimentation to reduce packet loss, enabling approximately 5 FPS, but this was at the cost of reduced reach. Therefore a conventional PoE, 48 V system using Cat5e cable was used for the tether system. The use of Cat5e cable enabled a tether length of 100 m to be utilized without noticeable packet loss, giving a frame rate of 15 FPS. The maximum power transmission was limited by the PoE injector, to 75 W, utilizing CotS hardware, which already conformed to CE marking regulations. The required communication bandwidth for Vega was approximately 10 Mb/s, with the vast majority of this being required to transmit the point cloud from the 3D camera.

The tether system was initially mounted on a spool, on-board Vega, and deployed using torque control (shown in Figure 10), however it was found that this system significantly reduced the robot's ability to negotiate obstacles due to the greatly increased center of mass and it often became tangled in the track system of the robot. The tether system was therefore mounted on a spool, which was servo actuated using a Dynamixel XM430 servo, utilizing torque control at the base station end. The servo maintained a constant torque on the tether system to prevent an excess in deployed tether. The tether could also be reeled in with the servo actuation meaning that there was no need for the operator to touch the cable, which is advantageous in deployments where the tether may collect mobile contamination. To prevent damage to the tether and the potential for a short circuit from abrasion on the surface, the tether should be shielded.

The wireless version of Vega utilizes a 75 Wh battery pack in the form of a commercially available USB-C power bank. This battery was chosen because it was a CE marked product that could provide sufficient peak power, had sufficient stored energy to operate the robot for greater than 2 h at peak power draw, and had both charging and power regulation built in. The battery was externally mounted and secured with a Velcro strap, making it simple to remove and disconnect. This was important as for active deployments the operator would be wearing Personal Protective Equipment (PPE), which would include one or more pairs of gloves, limiting dexterity. The USB-C standard allows power delivery at a range of voltages, including 12 V, with the battery (RAVPower 45 W Super-C Series) capable of supplying 12 V at 3 A, 36 W.

Disposal routes for certain materials that enter a radioactive environment, in particular batteries, are not straightforward. This is complicated further with lithium chemistry batteries, due to the fire/explosive risk if the cells are punctured or crushed (Carlson et al., 2004; Gianni, 2019; Zhang et al., 2020). As a consequence it is highly desirable to ensure that the battery can be removed from the environment. To address this, when the robot is deployed in an active environment, the battery is mounted inside a polythene bag, which prevents it from becoming contaminated with any radioactive materials. When the robot is ready to be decommissioned, an operator can remove the battery from the robot and the polythene bag. This allows the robot to be decommissioned using standard waste routes (Jacoby, 2013; Sivaprakasam et al., 2020), with the battery available for free release provided the integrity of the polythene bag has been retained during deployment.

Vega draws 8.4 W in standby mode, 13.2 W in stationary mapping mode and 16.8 W in mapping mode while moving at 0.05 m per second. This power consumption gives an operating life of 8 h 20 min, 5 h 20 min, and 4 h 10 min, respectively, which exceeds the required 2 h operating life, allowing for lengthy survey missions.

Vega is capable of recharging its battery in situ, via a charging dock, shown in Figure 2, which also includes the wireless router (with directional antennas). The charging dock utilizes contact based charging, which is activated by the operator once the robot is docked. At present the router and antenna combo are fixed in position, but future research is investigating a pan and tilt antenna tracking system for both the robot and base station which should provide improved communications range. The router (TP-Link CPE220) utilizes built-in 9 dBi 2 × 2 dual-polarized directional antennas with a beam width of 65 degrees (H-Plane) and 35 degrees (E-Plane), which provides a large operating window for the robot to work in, provided the base station is directed in the approximate direction of the robot. Vega presently utilizes omni-directional antennas.

5.2 | Onboard processing

Vega utilizes an X86 based, low power, small form factor computer for high level computation, and an ARM based microcontroller board for low level, real-time based computation, with the microcontroller board controlling two Dynamixel XM430 servos, used for

FIGURE 2 Vega docked to base station. Base station features include a directional antenna for a high power router, an omni-directional antenna for a local hot-spot router, and Ethernet connectivity and power supply [Color figure can be viewed at wileyonlinelibrary.com]

locomotion. The microcontroller board also provides a "dead man" function to be implemented in real-time, rather than being subjected to nondeterministic timing on the high level computer. If the microcontroller board lost communication with either the high level computer or the operator, the "dead man" function would stop the robot, preventing any collisions. The microcontroller board also features a DC/DC converter and is a CE marked component.

The overall cost of the Vega robot, comprising the hardware described in Sections 5.1 and 5.2 was approximately £1500, thus meeting the requirement for it to be below £2000.

5.3 | Manipulator

Vega was designed to be outfitted with a small 5 Degree of Freedom (DoF) manipulator, based on the Robotis OpenManipulator, mounted as shown in Figure 3. The purpose of this manipulator was to perform operations such as taking swabs of equipment and infrastructure for characterization purposes and to collect small samples (<500 g) during missions when necessary. The OpenManipulator arm was tested for repeatability and found to have a repeatable point accuracy of ±7 mm in 3D space, with a 400 g payload. The arm was further tested with payloads of up to 800 g, and found to have a repeatable accuracy of ±15 mm. Repeatability is important as when Vega is taking swabs it will need to wipe the end effector over the same section of a surface several times and an error of under approximately 20 mm was considered reasonable by technical staff working in the nuclear industry.

5.4 | Radiometric sensors

As required in the design specification, Vega was designed to be agnostic to the sensor payload it carries. To enable this the robot features Ethernet, USB 2.0, USB 3.0, SPI, UART, I2C and CAN I/O, along with externally accessible 12 and 5 V power busses, and internal 3.3, 5, 9, 12, 15, and 20 V power busses. A 48 V power bus is also available on the tethered version.

Engagement with nuclear end-users has suggested that different establishments tend to have preferred radiation detectors and it was therefore important that Vega was designed to be compatible with a number of common detection systems. A common detector that is used in the UK nuclear industry is the ThermoFisher Scientific RadEye G10 Gamma detector. This detector was successfully integrated onto Vega using a custom made ROS package for communication, via a USB to IR interface and demonstrated in an inactive test for Sellafield Ltd. (discussed in Section 7). The ThermoFisher Scientific RadEye SX sensor for external scintillation probes, designed to monitor Alpha/Beta radiation has also been successfully implemented using the same ROS library, which is described in Bird et al. (2018).

ThermoFisher Scientific personal dosimeters (EPD-N2 gamma-neutron dosimeter and EPD-MK2 dosimeter) have successfully been implemented on the robot, shown in Figure 3, and used in tandem with a RadEye G10 in an active deployment at the Dounreay facility (discussed in Section 7).

The Imitech CC-RIAS gamma spectrometer, shown in Figure 4, has also been integrated with the Vega robot and work is progressing with Createc to integrate their N-Visage Recon collimated gamma spectrometer sensor, shown in Figure 4.

5.5 | Dumb Vega (D-Vega)

As discussed in Section 3, the nuclear industry required an explicitly radiation hardened version of Vega, capable of prolonged use in high dose rate environments. For deployments into high dose areas an additional factor that needed to be considered was the effect of radiation on Vega. In particular, the electronic systems used in Vega will be damaged by gamma radiation (Nancekievill et al., 2016). During the clean up operations at Fukushima-Daiichi, several robots

FIGURE 3 Vega, in wireless form with manipulator, ThermoFisher RadEye G10 Gamma sensor, LiDAR and 3D Camera [Color figure can be viewed at wileyonlinelibrary.com]

FIGURE 4 Createc N-Visage Recon collimated gamma spectrometer (left), Imitec CC-RIAS collimated gamma spectrometer (right) [Color figure can be viewed at wileyonlinelibrary.com]

were subjected to absorbed doses in excess of 10 Gy/h (Zhang et al., 2020). This is a particularly high dose rate and a number of robots at Fukushima Daiichi are believed to have failed as a result of radiation exposure.

Individual component testing has been conducted on the components that make up Vega, to determine their tolerance to TID, and the results from this are provided in Section 6. The experiments showed that Vega is capable of operating in relatively high dosage environments for long periods without becoming disabled. However, to be able to operate effectively for sustained periods of time in relatively high dose rate environments, it may be necessary for the robot to be tolerant to a TID of tens of kGy and therefore other designs needed to be considered.

There are a number of approaches that have been adopted for protecting robots against the damaging effects of radiation. One approach is to use specifically designed radiation tolerant components, which has been successfully applied to robots used in space missions, such as the Curiosity Mars rover (Hassler et al., 2014). However, in space applications the damage typically results from single-event upsets (Hassler et al., 2014; Sauder et al., 2017; Zhang et al., 2020), whereas in nuclear decommissioning the damage results from the TID that the electronic device receives. The cost of using radiation hardened components can also be several orders of magnitude more expensive than their CoTS equivalent and typically restricts the use of technology to devices that are at least one or two generations behind latest state-of-the-art (Houssay, 2000).

An alternative approach to radiation-hardened components is to use shielding to protect the sensitive electronic components. The amount of shielding required would be dependent upon the dose rate within the environment, but to significantly reduce the dose rate, it would require several centimeters of high density material, which would add considerably to the weight that Vega would need to carry. The approach taken with Vega was to remove as much of the electronic systems from the robot as possible. For example, relay electronics were introduced and DC motors which did not require encoders were utilized. This allows Vega to, in theory, be deployed into high dose rate environments, albeit with reduced functionality, for example, wireless communications would not be possible. An additional factor that has not yet been considered with Vega is the radiation tolerance of the materials used in its construction. For example, considerable care will need to be taken on selecting the polymer coating for the wires and ensuring PTFE is not present in any of the equipment, as this is particularly sensitive to gamma radiation (Holmes-Siedle & Adams, 2002). This will be considered in future work. The target payload for D-Vega was a radiation hardened camera probe, with its own tether system and therefore no additional sensory equipment was required.

A 12 V sealed lead acid battery was used on-board D-Vega to power the two DC motors, which enabled differential drive. This battery was chosen due to its robustness and the technology's ability to function without regulatory electronics. As discussed in Section 5.1, a lead acid battery can be disposed of easier than a lithium based battery. The DC motors were controlled by relay constructed H-bridges. The H-bridges were signaled via a 100 m tether system, composed of relatively thin (26 AWG) wire. This set up was chosen because a tether system of the length required would have had to have been substantial in thickness to prevent the voltage drop under load from effecting the performance of the DC motors, which operated on 12 V. Each DC motor would need two cables for positive and negative, requiring a four-core tether. Another solution would have been to take into account the voltage drop under load and power the DC motors with significantly higher voltage from the base station side. This was not chosen as it would cause the DC motors to spin significantly faster under low load, which could potentially cause damage.

The relay solution allows the motors to be driven at a reasonably constant 12 V (battery charge depending), which is within their design specification, and allows for a thin tether system (again composed of four wires, but significantly thinner and lighter) to be used.

Similar solutions to this problem have been proposed by Saunder et al. (2017) for NASA, to explore the planet Venus. While radiation conditions are different to those experienced in nuclear environments, the temperature and pressure a robot is exposed to in the Venetian atmosphere introduces considerable challenges when using conventional electronics. Saunders et al. proposed vacuum tube electronics rather than conventional electronics, however this would increase the power requirements for the robot, as vacuum tubes require an electrical element to operate, which draws substantial current.

Unfortunately, without considerable development work, closed loop control of the DC motors could not be implemented at this stage as it would require the encoders in the motors to be replaced with resolvers, as the encoders would be susceptible to radiation damage in the target environment (Zhang et al., 2020), which is the subject of on-going research.

6 | INDIVIDUAL COMPONENT RADIATION TESTING

Electronic components are susceptible to radiation damage through a number of pathways, such as but not limited to; TID; neutron and proton displacement damage; and single event effects (SEE). Hardening electronics to withstand radiation damage requires considerations at the low level design state, which is expensive and time consuming. This typically means that radiation hardened electronics lag behind their consumer equivalent by a generation or more (Leroux, 2019).

The most pertinent damage pathway in nuclear decommissioning is TID, which is caused by the energy deposited in the electrons of the substrate of the electronic components by γ radiation (Di Buono et al., 2020). Therefore, testing the components that make up the Vega robot to determine the maximum TID they can sustain will give an indication of their survivability in a nuclear decommissioning environment.

To determine the minimum radiation dosage that would cause the Vega robot to fail, the electronic components that make up Vega were individually exposed to ionizing radiation of known dose rates. This exposure was undertaken using a Foss Therapy Services Model 812 Cobalt-60 Gamma Irradiator. The performance of each component was monitored continuously, while powered, throughout the irradiation to determine the total absorbed dose, measured in Gy, at which the performance of the component deteriorated to the extent it was no longer able to function effectively. Cobalt-60 Gamma Irradiators are the defacto industry standard for evaluating performance of electronics in terms of TID, as per the MIL-STD-883K standard for testing electronic devices for suitability in military and space environments.

It is of note that while some electronic components instantaneously failed at a given dose, others lost functionality gradually over a TID range. Where a TID range is quoted in the results table, this range is to be taken as being the lowest TID at which functionality of the component was noticeably impaired to the TID at which complete failure was confirmed. A single TID figure reflects observation of an instantaneous failure by the component.

The absorbed dose rate at the center of each component was determined using a Radcal Corporation Accu-Dose+ base unit equipped with a 10 × 6-0.18 ion chamber. This ion chamber was calibrated shortly before the tests by Public Health England to traceable international standards. The dose rates used were between 6.4 and 41.3 Gy/min depending on the optimum experimental arrangement for each of the components.

The literature (Houssay, 2000) suggested that the TID at which the individual components would fail, would be far in excess of the maximum TID that Vega was designed to operate in. For this reason, a single BoM worth of components for a single Vega were used, to validate these findings, without needlessly destroying valuable components. The components tested were therefore a pair of Dynamixel servos, a single Intel Realsense camera, a single RPLiDAR A1 and a Aaeon Intel Up Single Board Computer.

It should be noted that the Realsense D435i camera, gave a static filled RGB image that was unusable whenever it was exposed to ionizing radiation of 6.4 Gy/min, however the quality of the image did recover completely when the ionizing radiation was removed. The depth image was unaffected until the camera had received a TID of between 240 and 314 Gy, when the Realsense D435i camera suffered permanent failure to the communications systems preventing RGB or depth images to be taken. The TID at failure and the failure modes for the components are shown in Table 1.

All individual comments were power cycled in an attempt to bring them back online, however this did not achieve any positive results. The minimum absorbed dose at which individual components of Vega sustained damage was 82.6 Gy, which is consistent with the literature (Di Buono et al., 2020; Houssay, 2000; Leroux, 2019). This exceeds the required specification of being able to operate in a high dose rate environment, of 2 Gy/h for 8 h, which would give a TID of 16 Gy. Potentially, this would allow Vega to operate within the hotspot identified within a pressurized water reactor for up to 41 h.

7 | CASE STUDIES

Vega has been successfully deployed in both active and non-active environments at a variety of nuclear facilities in the United Kingdom, all while being tele-operated. Active deployments include a survey of

TABLE 1 Single component irradiation results, showing TID and failure modes

Device	TID before failure	Failure mode
Intel Realsense D435i	240.8–314.3 Gy	Communication errors before total loss of communication with device
RP LiDAR A1	220.5–264.6 Gy	Range of output periodically deteriorated before total loss of communication
Robotis OpenCR Driver Board	367.1 Gy	Total loss of communication with the device
Robotis Dynamixel W350	82.6, 88.4 Gy	Total loss of communication with the device
Aaeon Intel Up Board	100.8 Gy	Shutdown of device

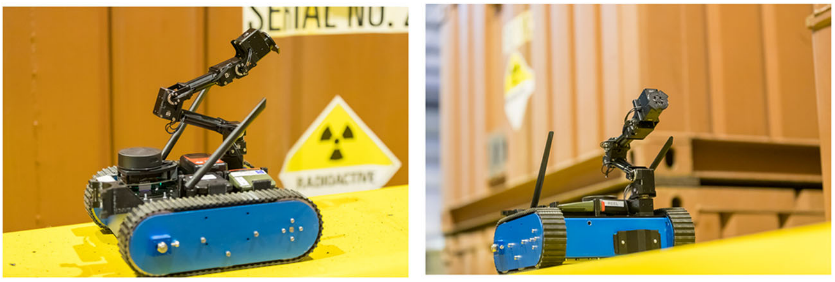

FIGURE 5 Vega with manipulator, during active deployment in the Dounreay waste store [Color figure can be viewed at wileyonlinelibrary.com]

FIGURE 6 Vega, demonstrating locomotion over rough terrain [Color figure can be viewed at wileyonlinelibrary.com]

a waste store at the Dounreay site in Scotland, United Kingdom, which was a prerequisite to a future active deployment. An image from this deployment is shown in Figure 5. Vega has also been successfully deployed in nonactive facilities in preparation to moving to active facility deployments at various UK nuclear sites. Images from two of these tests are shown in Figures 6 and 7, respectively. Furthermore, Vega is undergoing evaluation studies for active deployment at Sellafield in the United Kingdom, with a view to deployment on site in the future. For each of the deployments, the operator console was a relatively small case containing a computer, screen, keyboard and handheld controller.

A significant portion of the inactive deployments took place on the AWE site and the University of Bristol. Examples of two early deployments are shown in Figures 8 and 9. Both figures show a sealed gamma radiation source that has been located within the environment inside a bright red container. The radiation source used in this test was naturally occurring radioative material (NORM) and the aim for these tests was to test the ability of Vega to identify, locate and characterize this radiation source. To complete the test an Imitec CC-RIAS gamma spectrometer (shown in Figure 4) was integrated onto Vega. The CC-RIAS contains a collimated gamma spectrometer, which is able to measure up to 30,000 counts per second (cps) of gamma rays with energies of between 30 keV and 3.0 MeV. The maps produced by Vega are shown in the right hand side images in Figures 8 and 9. These show the ability of Vega to produce 2D and 2.5D point clouds of the environment, which can be displayed to the operator in real-time.

The CC-RIAS is equipped with both a short-range LiDAR and radiation detector and is able to raster over an area to create a 3D map superimposed with radiation measurements. The map produced during a scan is shown in the right-hand side of Figure 10. This scan shows the relatively higher gamma count rate that was produced by the sealed radiation source, allowing the location and intensity of gamma material to be located. Furthermore, the left hand side image in Figure 10 allows the radioactive material to be characterized. The decay sequence within a NORM sample is complex, but with ^{238}U present, it would be expected that gamma rays would be produced with energies of 352 keV for ^{214}Pb and 609 keV for ^{214}Bi Peaks at these energies can be seen in Figure 10, indicating that the source is NORM, containing ^{238}U.

Due to the COVID-19 pandemic, further active deployments of Vega have been paused, however plans are progressing to deploy Vega at the Dounreay site to inspect and characterize approximately 100 m of under-floor drain, which resides within the Fuel Cycle Area. The purpose of this deployment is to identify any radioactive materials that may be present in the drain, and if appropriate, swab sections of the drain for later analysis, allowing Dounreay Site Remediation Ltd (DSRL) to develop a mock-up of the drain and develop decommissioning techniques that will safely clean up the drain and surrounding area. Any swab samples will be taken using the manipulator arm shown in Figure 3.

8 | LONG-TERM DEPLOYMENT AND DECOMMISSIONING CONSIDERATIONS

While Vega was designed to be low cost and potentially disposable, it is capable of remaining in situ indefinitely. This feature is available in both the wireless and tethered versions of the robot. This enables lengthy surveys of complex environments to take place over multiple days or weeks.

In such deployments, Vega is intended to be parked in a safe location (with as much passive shielding provided by the environment as necessary and reasonably possible) and shutdown. In the case of the wireless version of Vega, it can be parked on its dock to recharge, as shown in Figure 2.

Once the plant or environment is ready to be fully decommissioned and Vega is no longer required, an operator can remove the battery by releasing the Velcro strap and Vega can then be processed appropriately (Haskins, 1995; Zhang et al., 2020).

While some effort was placed in minimizing contamination traps, some traps remained as the cost of engineering the design to remove them was considered to be too high. To determine how much contamination it may collect during a deployment, testing was performed using fluorescent rodent tracking powder, as shown in Figure 11. The rodent tracking powder is a fine dust which fluoresces under

FIGURE 7 Vega, in tethered form with common sensor configuration, LiDAR and 3D Camera, being demonstrated at an inactive test for AWE in the United Kingdom [Color figure can be viewed at wileyonlinelibrary.com]

FIGURE 8 Fenswood (University of Bristol) inactive test for AWE. Left image shows Vega positioned beside a gamma source (red disk), with Imitec CC-RIAS mounted as payload. Right image shows an example of the live point cloud produced by the robot, which can be saved and evaluated at the operators discretion. Note the gamma source highlighted in red, and the two barrels highlighted in green [Color figure can be viewed at wileyonlinelibrary.com]

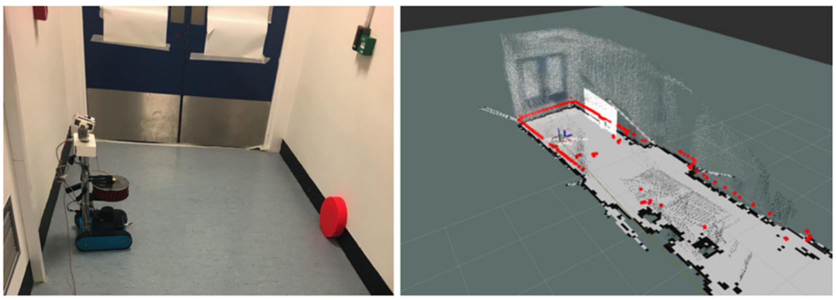

FIGURE 9 Inactive test at University of Bristol for AWE with Vega. This inactive test demonstrated the Imitec CC-RIAS integration. Right image shows the telemetry output of the robot, note the persistent point cloud generated from RTAB mapping, the live 2D planar LiDAR (red) and the live 2.5D point cloud (white), which are both relayed in real-time to the operator, together with a live video stream from the forward facing camera [Color figure can be viewed at wileyonlinelibrary.com]

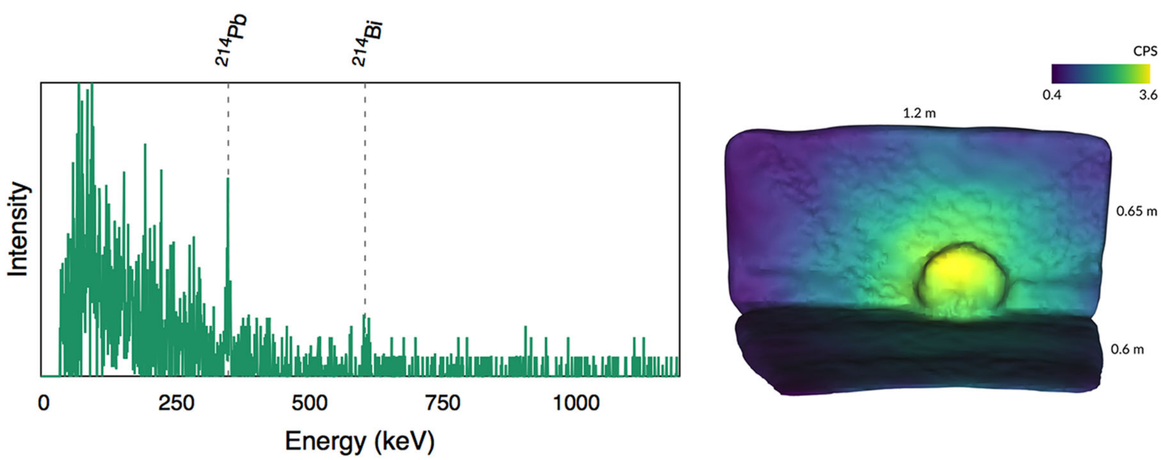

FIGURE 10 Output of Imitec RIAS, showing source energy spectrum (right) and point cloud output with source intensity overlayed as RGB values [Color figure can be viewed at wileyonlinelibrary.com]

FIGURE 11 Contamination testing using fluorescing rodent tracking powder [Color figure can be viewed at wileyonlinelibrary.com]

ultraviolet light. The dust was believed to be a comparable substitute to the fine oxide particulates that would be expected in a decommissioning environment (Haskins, 1995). The contamination testing work is discussed at length by Banos et al. (2021), where the cleanup effort was compared to that required for a Hexapod robot. The Hexapod robot was found to spread the contamination significantly less due to its smaller ground contact area, however, as with Vega the contamination was difficult to remove completely.

The rodent tracking dust was dispersed into a $1.2 \times 1.2\,m^2$, and Vega was driven through. The $1.2 \times 1.2\,m^2$ provided enough contact surface to ensure that the entire track length of the robot was covered. Vega was then moved out of the area and the spread of the dust was observed. This is shown in Figure 11.

Vega was then cleaned by operators wearing thick rubber gloves, to simulate an operator cleaning the robot of contamination in a nuclear environment. Cleaning was conducted using "wet wipes" and after 30 min Vega was observed under a UV light. Significant contaminating dust was still present on both the chassis, internals of Vega and the track mechanism.

Vega was then further cleaned with spray bottles and wipes, by operators without the thick and cumbersome gloves. After a further 30 min Vega was again observed under a UV light and it was found that contaminating dust still remained.

From these tests it was considered impractical for Vega to be cleaned of contamination after a deployment where there may be mobile contamination in the form of fine powders. It would therefore be expected that Vega would be used as a sacrificial robot, or it would remain within a facility following deployment for subsequent reuse.

9 | LESSONS LEARNED

A great many lessons were learned in the development of Vega and we have tried to summarize the most important of these below:

1. There are an enormous variety of challenges in the nuclear industry, where robots may provide a solution. To ensure that a generic solution is identified it is important to engage with a broad range of experts and operational staff at multiple sites to enable the generic features of these challenges to be identified and the specifications for a robot identified.
2. While robotic solutions for nuclear environments may share common properties to robots designed for other industrial environments, an important difference is that it is not possible to thoroughly test the capabilities of nuclear robots without the ability to test in radioactive environments, which can be very difficult to access.
3. Deploying new robotic technologies into radioactive facilities on nuclear sites is not straightforward given that the industry is highly risk averse and considerable effort must be focused on identifying opportunities across multiple sites.
4. The need to test the capabilities of a robot in an on-site radioactive facility means that other design aspects, such as UKCA or CE marking need to be considered from the initial design stages.
5. When deploying robots into legacy facilities it is not uncommon for precise inventories and details of the plant, for example availability of access ports and dimensions of a facility, to be uncertain and therefore some flexibility, in for example sensor payload or size of object the robot can traverse, is required in the capabilities of any robot that is developed.
6. Electronic components are tolerant to the ionizing dose rate that is found in many nuclear decommissioning environments. As such, bespoke radiation shielding and radiation hardened electronics are often not required.
7. Tether systems are typically preferred by the nuclear decommissioning industry in the hope that the robot can be retrieved should problems occur. Unfortunately, once a robot has moved beyond visual line of sight and around multiple corners or obstructions, retrieval using a tether may not be possible. Tether systems also present many additional hazards such as the tether becoming tangled or it affecting the characteristics of the robot, such as raising its center of gravity. It is anticipated that as experience with robotic systems in the industry increases, then non-tethered systems will become accepted.

10 | CONCLUSION

This paper has described the development process that was followed to create a small, low-cost robot, Vega, that is able to perform characterization operations within nuclear decommissioning environments. To ensure that Vega was suitable for deployment in generic nuclear environments, it has been developed in close collaboration with a number of UK nuclear end-users, who helped to generate a comprehensive list of specifications for Vega. Vega was able to fully meet these specifications and, in particular, it was designed with CE marking considered from the first stages of development.

A variety of radiometric sensors have been successfully integrated onto Vega, enabling it to perform a range of radiation surveying tasks. These sensors, along with its built in 3D camera and 2D Planar LiDAR enable Vega to generate complex maps and 3D point clouds of its environment, which can then be overlaid with radiometric, or other survey data. The 3D environment can be measured online, to determine obstacle characteristics to enable safe maneuvering of the robot in its environment. Vega was designed to be flexible in its payload and it can be outfitted with various sensors and actuators, including gamma spectrometers, alpha/beta radiation sensors, LiDARs, lighting and a small robotic arm.

Vega has been designed to perform tele-operated exploration over challenging terrains using an X86 based on-board computer, a large array of sensors and differential drive continuous tracks. It has been successfully deployed in an active environment at the Dounreay facility in the United Kingdom and has been successfully deployed in a non-active environment at the AWE, also in the United Kingdom. Trials with the robot have also been conducted, with a view to deploy in active environments with Sellafield Ltd and other nuclear site license companies in the United Kingdom.

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