Towards Expendable Robot Teaming in Extreme Environments

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***Abstract*—In this work we introduce the concept of *expendable robot teaming* and its relevance in domain applications where the magnitude of hazards and risks reach the point that human exposure represents either a direct threat to life or long-term health consequences. We also introduce the main rationale behind this alternative approach to multiple robot deployment in extreme environments with particular attention to nuclear waste management and decommissioning. Finally, we briefly discuss related research challenges and directions.**

***Index Terms*—multi-robot systems, extreme environments, autonomous robots, communication networks, machine learning, nuclear waste, decommissioning, radiological instrumentation. robot coordination and cooperation**

I. Expendable Robot Teaming: Concept, Relevance and Rationale

In the last decade, the employment of teams of heterogeneous robots in extreme environments has significantly increased [1-6]. Unlike single robot deployment, multiple robots can cooperatively perform more complex activities in less time [7-10]. Their heterogeneity also guarantees that a wider spectrum of tasks and domains can be covered [10-12]. Robots can reach areas not easily accessible to humans and can prevent exposure of humans to hazards which may represent either a direct threat to life or long-term health consequences [6].

Despite these great advantages, the deployment in extreme environments of a team of heterogeneous robots that are effective, reliable, fault tolerant, resilient and able to autonomously cooperate is still far from being developed in practice. The reason for this is that extreme environments especially those where hazards are present in the form of radiological or toxicity dangers, such as nuclear materials and waste, introduce challenges that current research in the field of Artificial Intelligence, Machine Learning and Robotics are not able to properly address yet.

Nuclear decommissioning and the safe disposal of nuclear waste is a global problem of enormous societal importance [13]. The UK alone contains 4.9 million tonnes of legacy nuclear waste, representing the largest, and most complex, environmental remediation project in the whole of Europe [15]. It has been estimated that the process of cleaning-up the UK's million tonnes of waste is expected to take over 100 years with current annual costs exceeding £3 billion and that these costs are expected to rise over time. In Table I we report the general classification of the nuclear waste depending upon the degree to which it is irradiated together with its disposal route [16].

TABLE I. Classification of Radioactive Waste and Disposal Route

Category	Disposal route
Very Low-Level Waste (VLLW)	Close to natural radioactivity. Its activity is less than 100 becquerels per gram. It consists of rubble (e.g., concrete, plaster, soil), scrap metal (e.g., metal structures, pipes) or components from nuclear power plants, such as steam generators. Accounts for about 70% of the volume. Can be disposed of in normal landfill sites.
Low-Level Waste (LLW)	Contains relatively low levels of radioactivity, not exceeding 4 gigabecquerel (GBq) per tonne of alpha activity, or 12 GBq per tonne of beta/gamma activity. Includes items such as scrap metal, paper and plastics. Some smaller amounts also come from hospitals and universities. Accounts for about 94% of the volume. Typically stored on-site by licensees, either until it has decayed away and can be disposed of as ordinary trash, or until amounts are large enough for shipment to a dedicated site in containers approved by the Department of Transportation.
Intermediate-Level Waste (ILW)	It exceeds 4 gigabecquerel (GBq) per tonne of alpha activity, or 12 GBq per tonne of beta/gamma activity but does not generate a significant amount of heat (< 2 kW/m3). Typically comprises resins, chemical sludges from the treatment of radioactive liquid effluents, and metal fuel cladding, as well as contaminated materials from reactor decommissioning. Smaller items and any non-solids may be solidified in concrete or bitumen for disposal. It makes up some 7% of the volume and has 4% of the radioactivity of all radioactive waste. It requires shielding. No dedicated facility in the UK at present [16]. Potential interim storage sites are located at AWE Aldermaston, AWE Burghfield, Capenhurst (CNS), Sellafield (NDA) Chapelcross (NDA) [14].
Higher-Level Waste (HLW)	It is radioactive enough for the decay heat to increase significantly its temperature and the temperature of its surroundings. It includes the liquid residue that contains most of the radioactivity from the reprocessing of spent nuclear fuel, this residue once it has been solidified due to a vitrification process or any other waste with similar radiological characteristics. Accounts for no more than 3% of the volume. Requires special storage with cooling.

The Ministry of Defence (MOD) in the UK has seven decommissioned submarines currently stored afloat at Rosyth Royal Dockyard in Scotland, and thirteen at

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Devonport Royal Dockyard in Plymouth [17]. The submarines can only be completely dismantled once the radioactive material and components have been safely removed [18].

The accident at the Fukushima Daiichi Nuclear Power Plant (FDNPP) in Japan on March 11, 2011 resulted in a release of about 73 radionuclides (135 in total including radioactive progeny). During the following days, hydrogen explosions released large amounts of radioactivity into the atmosphere. Fearing more severe damage and larger releases, plant managers ordered seawater to be used as a cooling medium. This highly radioactive water was discharged to the Pacific Ocean, with discharges (to both land and sea) ongoing more than three years following the accident [19]. Despite the tremendous technological and financial efforts in Japan to deal with the effects of the FDNPP accident, cleanup operations to remove contaminated water, to keep out the inflow of water into the sources of contamination and to prevent leakage of contaminated water into the environment are still ongoing [20].

Another area for decommissioning is that of many offshore North Sea oil and gas fields which are reaching the end of their lives [21]. This includes 6 fields on the Danish Continental Shelf, 23 fields on the Norwegian Continental Shelf (NCS), 106 fields on the Dutch Continental Shelf and 214 fields on the UK Continental Shelf (UKCS). From 2017 to 2025, across the four regions, over 200 platforms are forecast for complete or partial removal, close to 2,500 wells are expected to be plugged and abandoned and nearly 7,800 kilometres of pipeline are forecast to be decommissioned [22]. The cost and complexity of carrying out this work is one of the oil and gas industry's largest ongoing challenges [23]. Given the costs involved in offshore decommissioning, several research institutes are looking for methods to make offshore oil platforms "clean" and able to support marine life as an alternative to full removal (e.g., bringing disused oil platforms into shallow water and using them as artificial reefs or making them clean and safe, and then leaving them [24]).

Multiple robots deployment in the domains and the scenarios mentioned above pose several crucial problems that have not received adequate attention. First, sensors like LIDARs, RGB-D and infrared cameras, commonly used on current robotic platforms for 3D mapping and visual perception, are unable to provide information about invisible phenomena such as radioactivity. Second, ionizing radiations can damage the robots' electronic components leading to malfunctions and to strongly corrupted measurements from sensors [25]. Another issue concerns communication between robots. Usually the structures of nuclear facilities can be of particularly thick concrete walls, they sometimes can include lead or they can be of carbon steel [26]. These structures prevent the use of the standard communication network infrastructures and protocols currently adopted in multi-robot systems [27]. Moreover, the equipment necessary for communication (e.g., antennae, relays) can often not be set up.

Accessibility and reachability of particular areas of a nuclear facility that need to be inspected represent another interesting challenge for a team of heterogeneous robots. It will suffice to consider the example of traversing the pipes to reach the reactor of a nuclear submarine to check for possible leakages rather than navigating into contaminated water to determine the presence of residuals of fuel debris and corium [19]. Last, but not least, the temporary or definitive loss of robots due to contamination must be considered. After their use, robots must be put in sealed containers and sent to a processing facility. Here, they must be security declassified and final reassurance monitored to ensure that no radioactivity is released before their next possible reuse. This represents an additional cost to the dismantling and decommissioning management process, that must be included in costing.

The challenging domain applications previously introduced together with the above considerations motivated us to push towards the concept of expendable robot teaming. Expendable robot teaming refers to a team composed of robots of different size (e.g., tiny, small, medium, large), locomotion systems (e.g., tracked, wheeled, legged, flying, underwater), sensors, electronics, power systems, payload and price, some of which can be left on-site in case of fault or contamination, without the need to be retrieved or repaired and without representing a significant loss in terms of cost of the technology and of the disposal process. Such a feature depends upon the relations which can be established between the different characteristics of the robots of the team and the degree of complexity, dimension, type, accessibility, reachability and the expected level of radioactivity of the different areas of a nuclear site. Moreover, by means of their design in term of both size and mobility, these robots have the characteristic that some of them can be carried or lifted by others [28].

II. Expendable Robot Teaming in Extreme Environments

In Fig. 1 we show an example of how the accessibility and reachability of different areas of a nuclear site depend upon the locomotion system and size of robots.

Let us consider, for example, the large tracked vehicle Guardian [29], the small wheeled robot Vertigo [30] and the medium-size ape-like robot RoboSimian [31] depicted in Fig. 1. It is worth noting that these robots are endowed with a dual locomotion system. In fact, Guardian has two active sub-tracks and two wheels on both the ends of the main tracks. This dual locomotion system makes this vehicle suitable for off-road terrain navigation, debris and rubble negotiation and stair climbing. Vertigo has two tiltable propellers and four wheels. The propellers provide this robot with thrust onto the walls which enables climbing of cooling towers.

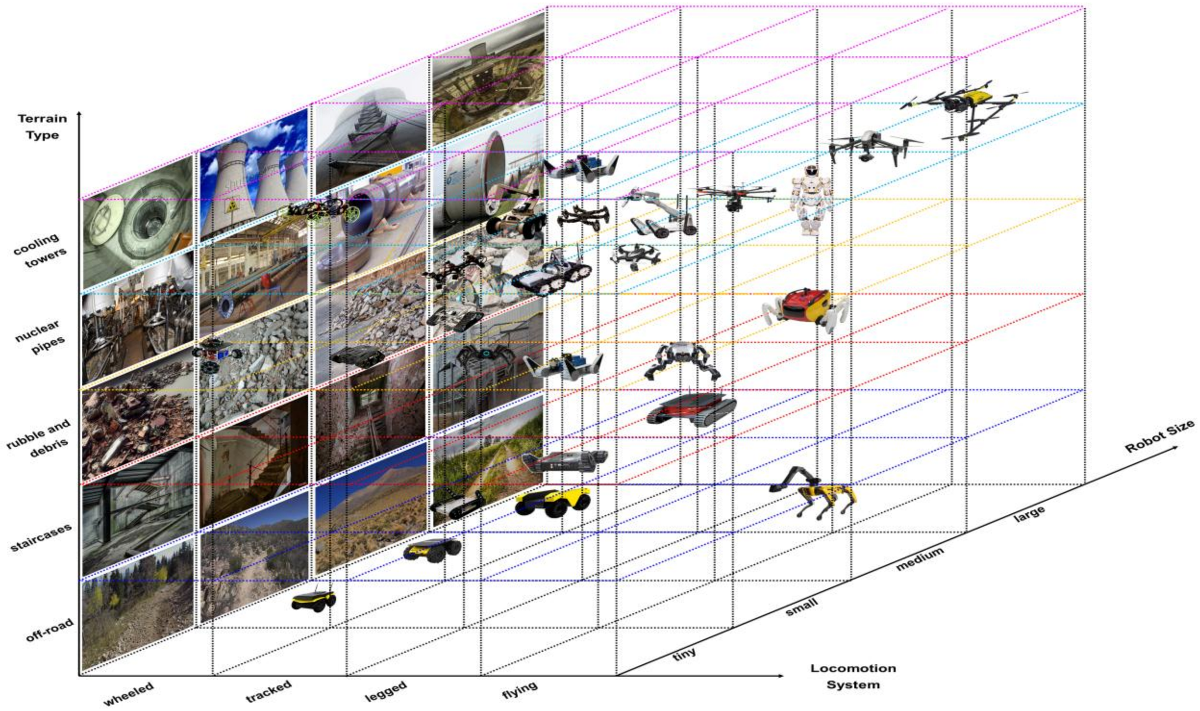

Figure 1. Correlation between the degree of complexity, dimension, type, accessibility, reachability of the different areas of a nuclear site and the robots' characteristics in terms of size and mobility.

RoboSimian is endowed with both limbs and hands through which this robot can accomplish both mobility and manipulation tasks.

The locomotion system of the medium-size tracked vehicles Gemini-Scout [32] and Absolem [33] includes multiple passive DOF links and novel track design. These characteristics provide these robots with a better traction on harsh terrains [34]. The mechanical design of the six-legged underwater robot Crabster CR200 [35] enables this platform also to handle hazardous materials, to move on land and to crawl over rubble and debris. The compliant feet of the small hexapod DIGbot [36] allow the robot to execute complex climbing manoeuvres on surfaces of any orientation with respect to gravity like in a reactor pressure vessel of a nuclear power plant.

Finally, also note in Fig. 1 how the use of robots with variable size and mobility is paramount, in particular for inspecting nuclear pipes of different diameter. Table II and Table III show an analysis of the radioactivity conditions under which a particular robot (among those depicted in Fig. 1) might operate and of the economic impact on the cost of the decommissioning process in the case in which such a robot was employed and it was left on-site. The latter aims at better clarifying the concept of expendability introduced in this work.

From the last column of Table II and Table III, it is clear that none of the robots mentioned in this work would be able to operate in the nearby of sources of HLW independently by their price. To the best of our knowledge, none of them is endowed with a shielding material which is resistant to the high temperatures generated by these sources (see Table I). All the robots could operate in the presence of either VLLW or LLW of solely alpha activity since any material provides shielding for alpha radiations. In the presence of both beta and gamma activities there are several issues to be considered. The materials used in the construction of very high cost robots may not prevent bremsstrahlung radiations being produced by the interaction with beta radiations. The materials may not protect against gamma radiations as they may be completely transparent to them or may also not be of the required thickness. This would create a disposal problem (see Table I). Therefore, it would be preferred that very high cost robots were not operating closely to either ILW or LLW of beta and gamma activity. Their temporary or definitive loss would represent a significant cost. For this reason, they should be considered non-expendable at least until "suitable" materials are adopted for shielding (see Section III).

Robots whose cost ranges from medium to high might be expendable members of a robot team for which the risk of fault and contamination due to the presence of either ILW or LLW beta and gamma activity is such that it would not constitute a heavy loss. They may be left on-site without any need for retrieval. Conversely, very low or low cost robots cannot be considered expendable even though their deployment in the nearby of sources of beta or gamma radiations would be preferred for size and mobility reasons related to accessibility and reachability (see Fig. 1). The motivation behind this distinction is due to the existing tradeoff between the price of the robots and their performance. Medium and high cost robots are endowed with electronic components which are probably more robust than their cheaper counterpart. The exposure to this kind of ionising radiation even for a few seconds would be already enough to immediately damage very low and low cost robots. Moreover, being cheaper than the others, very low and low cost robots would certainly have a limited and less accurate sensor suite. The above considerations give rise to three important issues: (1) how to make standard sensors resilient to radiations; (2) how to harden electronics and, finally, (3) what kind of measurement units could be used to enable the collection of all the radiological data necessary to characterize a facility. These aspects will be briefly discussed in the next section.

III. Research Challenges and Directions

1) Hardening electronics and shielding: In nuclear domain applications materials for shielding robots must meet several functional requirements [37].

First, they must protect robots against alpha, beta and gamma radiations. Any material can provide shielding for alpha radiations. Materials that have a low atomic number such as plastic, aluminum, acrylic and polyethylene, can protect robots against beta radiations. On the other hand, shielding materials required for gamma radiations need to have a higher atomic number and density like for instance lead, tungsten and depleted uranium. Due to its high atomic number, lead is not suitable to be used for protection against alpha, beta and gamma. It does not prevent the production of bremsstrahlung radiations. Conversely, acrylic on its own cannot be used to protect against gamma radiations as it is completely transparent to it. A study conducted in [38] showed that using materials with lower atomic numbers before materials with higher atomic number provided effective shielding against beta and gamma radiations. According to this study, a combination of acrylic and lead acrylic can be used to shield a robot against alpha, beta and gamma radiations. In this combination, acrylic must be placed before lead acrylic. Acrylic will attenuate the beta radiations and lead acrylic will attenuate the gamma ones. However, both lead and acrylic need to be encapsulated in a clothing material. Therefore, shielding materials must also be capable of being malleable to be shaped into clothes for the robot. Demron is a fabric which is more flexible and malleable than lead. It can provide reasonable protection from low energy gamma radiations and limited protection from medium and high energy gamma radiations [39]. These properties make Demron the most suitable material for developing the radiation protection clothing for the robot. Moreover, special attention must be paid to the type of joints applicable to materials for radiation protection. Joints can be of two types: (1) permanent (e.g., thin layers of fabric melted through laser welding to avoid damages to the outer surfaces) or (2) temporary (e.g., zip or Velcro to reduce at minimum the permeability). Temporary joints can be applied to all the materials. The thickness of the shielding materials is also an important functional requirement. It must be directly proportional to the energy of radiations. Finally, the materials for covering lens or thermal devices must be transparent. Acrylic is the most reasonable choice. Unlike other materials mentioned above, it is transparent and can protect against alpha and beta radiations.

TABLE II. Mapping between the Robots and the Different Areas of a Nuclear Site within Which They Should Operate Based on the Robots' Prices and on the Levels of Radioactivity in Table I.

Robot	Cost					Radioactivity Classes						
	Very Low	Low	Medium	High	Very High	VLLW	LLW			ILW		HLW
							α	β	γ	β	γ	
 IG32 DM	✓					✓	✓	✗	✗	✗	✗	✗
 Vertigo		✓				✓	✓	✗	✗	✗	✗	✗
 Jackal			✓			✓	✓	✓	✓	✓	✓	✗
 Husky				✓		✓	✓	✓	✓	✓	✓	✗
 Warthog				✓		✓	✓	✓	✓	✓	✓	✗
 Sentinel					✓	✓	✓	✗	✗	✗	✗	✗

Robot	Cost					Radioactivity Classes						
	Very Low	Low	Medium	High	Very High	VLLW	LLW			ILW		HLW
							α	β	γ	β	γ	
 Devastator	✓					✓	✓	✗	✗	✗	✗	✗
 MLT-42-F		✓				✓	✓	✗	✗	✗	✗	✗
 Jaguar V4			✓			✓	✓	✓	✓	✓	✓	✗
 Absolem				✓		✓	✓	✓	✓	✓	✓	✗
 Guardian					✓	✓	✓	✗	✗	✗	✗	✗
 Gemini-Scout				✓		✓	✓	✓	✓	✓	✓	✗
 0x-ALPHA				✓		✓	✓	✓	✓	✓	✓	✗
 T8X	✓					✓	✓	✗	✗	✗	✗	✗
 Digibot		✓				✓	✓	✗	✗	✗	✗	✗
 PhantomX		✓				✓	✓	✗	✗	✗	✗	✗
 SpotMini					✓	✓	✓	✗	✗	✗	✗	✗
 RobotSimian					✓	✓	✓	✗	✗	✗	✗	✗

Robot	Cost					Radioactivity Classes						
	Very Low	Low	Medium	High	Very High	VLLW	LLW			ILW		HLW
							α	β	γ	β	γ	
 Valkyrie					✓	✓	✓	✗	✗	✗	✗	✗
 Crabster CR200					✓	✓	✓	✗	✗	✗	✗	✗
 Nano Helicopter	✓					✓	✓	✗	✗	✗	✗	✗
 Matrice 600		✓				✓	✓	✗	✗	✗	✗	✗
 Inspire 2		✓				✓	✓	✗	✗	✗	✗	✗
 Falcon 8+			✓			✓	✓	✓	✓	✓	✓	✗

2) Nuclear Instrumentation: Radiological inspection is of vital importance throughout all the stages of the dismantling and decommissioning process of a nuclear site. However, this activity requires specialized radiological measurement units to enable a robot to quantify radiological activities and to collect all the information necessary to interpret the radiological spectra. These units must be able to perform three kind of surveys: (1) radiation survey; (2) contamination survey and, finally, (3) radionuclide identification.

Radiation surveys are performed to measure radiation dose rates, which are a measure of energy deposited in an object. Contamination surveys are used to survey for the presence of radioactive materials in a place that they are not expected to be. Radionuclide identification is performed to identify specific radionuclides present in a source or as contamination. For these purposes, the nuclear instrumentation of the robot must be highly sensitive to radiation as measuring the energy of alpha, beta and gamma radiation ranging from low to high is fundamental for contamination surveys. Moreover, it must be able to distinguish between radiation energies, as measuring radiation dose rate is necessary for radiation surveys. The nuclear instrumentation of the robot must also be able to classify the kind of radionuclides emitting radiation for their identification. The volume covered, the spatial resolution and the minimum distance allowed to detect the kind of radiological activity are also important features for the selection of the nuclear instrumentation of the robot. The wider the volume spanned by the radiological unit is, the greater the distance from the hazardous is, the less the dose and the energy of radiation which will hit the robot will be. Finally, the instrumentation must be lightweight and measurement dynamic. It must work at high temperature and it must be connectible with the robot via standard interfaces. Unfortunately, there exists no nuclear instrumentation which meets all the aforementioned functional requirements in a single device. Nonetheless, in the following we introduce some nuclear measurement units currently available on the market which meet some of them. iPIX is an ultra-portable high temperature gamma imaging system developed by CANBERRA [40]. This system can be used on a robot to locate and identify at real-time low level radioactive sources while estimating the dose rate at the measurement point. It is very light weight (~2.5kg). It has a high detection sensitivity even at low energies and it is fully decontaminable. CdZnTe is a large volume spectroscopy detector developed by RITEC [41]. By means of its spectroscopy performance like high efficiency, high energy resolution, room temperature operation, wide detection range and small dimensions and weight, this detector can be used for nuclide identification. GammaTRACER Series from Bertin Instruments are autonomous and hermetically sealed gamma dose rate probes for stationary and mobile use [42]. These devices integrate 2G/3G/4G, radio, satellite communication modules as well as GPS. They are designed for continuously measuring (with adjustable cycle times), recording and transmitting the environmental gamma dose rate. The APOC PRO produced by AeroSplice is a highly sensitive radiation sensor capable of detecting gamma and beta radiation [43]. This device is low voltage and it has been designed for the embedded systems market thus making it suitable for Unmanned Aerial Vehicles (UAVs).

3) Coordination and Cooperation: Coordination and cooperation of expendable robots for monitoring and inspection activities of a nuclear site (e.g., exploration, coverage and patrolling) need to account for several critical factors, of which the foremost is the communication (see Section I).

Long coaxial cables for remote handling communication can be ruled out as they would easily get stuck between the waste or the structural parts of the site. Wireless networks are not commonly used in nuclear installation as they would need to be adapted to hostile environments [27]. Hybrid communications involving both tethering and local wireless links (e.g., Zigbee, Wi-Fi, WiMAX, and LTE) seems to be an appealing solution [44], [45]. Due to the potential loss of a robot of the team the network topology changes. This problem must be addressed in order to keep the connectivity among the remaining robots of the team. Under this perspective, adaptive tree-based algorithms accounting for overhead reduction and low battery power consumption constraints shall be employed as mechanisms for efficient neighbour discovery and routing [46], [47].

Special attention must be also paid to knowledge management. It constitutes the basis of any mechanism of decision making underpinning coordination and cooperation. The first problem related to knowledge management regards the integrity of the perceptual information of the individual robots operating in a contaminated area. This integrity depends upon the amount of disturbances affecting the sensor readings. Such disturbances may vary as the kind of robot, the price, the sensor suite, the type of irradiation resistance and the operational distance from a certain type of radiation change. To mitigate this problem techniques based on signal-disturbance discrimination should be adopted [48]. Another issue concerns the merging of the percepts of the individual robots for environment modelling. These percepts may have different representations and may be of different kind depending on the perceptual systems which built them. Moreover, only a part of these percepts may require merging while another could be kept separated. Common memory structures based on hierarchies of ontologies are a compelling solution [49], [50]. In addition to merging, these structures also favour the consistency and the persistence of the models. Moreover, they can also be exploited for decision making and knowledge discovery especially in the presence of missing information [51].

Finally, coordination and cooperation of expendable robots in nuclear domain applications need to account for team formation and coalition also under a parent-child grouping paradigm. Parent-child grouping is of particular interest if we want to make the most of both the strengths and the weaknesses of the locomotion mechanisms of every single robot of the team to access and reach the different areas of a nuclear site. An explanatory example may be the one in which an area of the nuclear site potentially contaminated would be reachable passing through a narrow passage on the top of a staircase. Another case may be the one in which it would be necessary to inspect the interior of a pipe whose entrance is located in the middle of a cooling tower. In the first case, a platform similar to Absolem (parent robot) by means of its triple-track locomotion system could climb the stairs carrying a vehicle like Devastator [52] (child robot). Once on the top, Devastator could get off and enter into the narrow passage because of its smaller size. In the latter, a UAV (parent robot) could fly through the cooling tower and carry a light weight robot (child robot) up to the entrance of the pipe. However, modelling such a behavioural control is very challenging as the dynamics of this form of grouping is quite complex and unpredictable [53], [54]. Multi-Robot Reinforcement Learning (MRRL) would provide a huge advantage [55]. It would allow robots to grab appropriate behaviours and interactions, without relying on a complete model of the environment. This particularly would benefit expendable robot teaming when some of the robots are lost or the environment is changed.

IV. Conclusion and Ongoing Work

In this work we introduced the concept of expendable robot teaming in extreme environments. We describe the main principles and motivations underpinning this concept in relations to the different properties of an extreme environment. We analyzed several robotic technologies in relation to these types of environments, focusing our attention to nuclear sites, and we also derived general criteria which can be applied to determine whether a robot technology can be considered expendable. We finally report some of the most critical research challenges which must be carefully addressed when multi-robot systems are deployed in these environments.

We are currently using the concepts and principles of expendable robot teaming to develop a framework enabling a team of heterogeneous robots to build and maintain over time a collective and continuous spatio-temporal radiological assessment of nuclear submarine reactor compartments. The main purpose is to identify the presence of intermediate-level radioactive waste in the compartments after the removal of the nuclear fuel from the reactors.

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