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Modular Robots for Enabling Operations in Unstructured Extreme Environments

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Operations in extreme and hostile environments, such as offshore oil and gas production, nuclear decommissioning, nuclear facility maintenance, deep mining, space exploration, and subsea applications, require the execution of sophisticated tasks. In nuclear environments, robotic systems have advanced significantly over the past years but still suffer from task failures caused by informational and physical uncertainty of the highly unstructured nature of the environment and exasperated by the time constraints imposed by high radiation levels. Herein, a survey is presented of current robotic systems that can operate in such extreme environments and offer a novel approach to solving the challenges they impose, encapsulated by the mission statement of *providing structure in unstructured environments* and exemplified by a new self-assembling modular robotic system, the Connect-R.

1. Introduction

As we push the boundaries of human endeavor, we will inevitably operate in more extreme environments than ever before, including nuclear zones, offshore environments, space exploration, defence, subsea applications, and deep mining. Operations in these hostile, extreme environments require the execution of sophisticated tasks such as deploying systems for inspection, lifting, and cutting. The nature of these environments increases the risk to human life and consequently inflates the cost of operations. The urgency to remove people from these environments has driven industries to look for more cost-effective and safer methods to conduct operations and inspection tasks. Advances in robotics and automation have led people to believe that robots can provide the capability required for these tasks.

Here, we focus on how the current advancement of the field of robotics can affect immediate change in performing these tasks in extreme environments, specifically nuclear commissioning environments. This particular extreme environment has a unique temporal constraint imposed on operators due to the total integrated dose imparted by high levels of radiation, which are of course too severe for human operators, leaving robotics as the only viable solution. **Figure 1** shows the total integrated dose for 23 different nuclear robotic systems and the amount of time (hours) the robots are able to operate for in a specified nuclear environment (Fukushima Daiichi Unit 2 Reactor). The total integrated dose is the total amount of radiation dose that a robot can withstand

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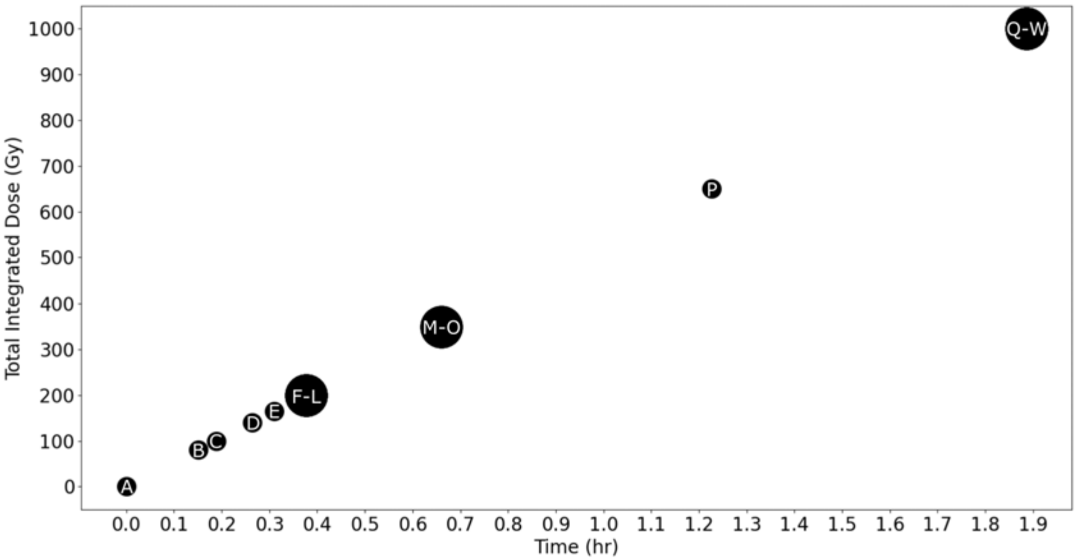

Figure 1. Total integrated dose (TID) of 23 different nuclear robotic systems and the effective time (hours) before failure in the Fukushima Daiichi Unit 2 Reactor (530 Gy h^{-1}). (A) Humans (for comparison) (0.02 Gy).[76] (B) Shape-changing robot.[77] (C) AVEXIS.[78] (D) DRV.[79] (E) KUKA iiwa LBR robot.[80] (F) Qunice 1.[81] (G) Quince 2.[82] (H) Quince 3.[83] (I) SC-ROV.[79] (J) Gengo.[79] (K) Trydiver.[79] (L) Underwater ROV.[79] (M) Mini Rover M $\approx$ K I.[84] (N) The Phantom 300 XTL.[84] (O) General Electric's Minisubmarine.[84] (P) Scorpion.[85] (Q) TEPCO cleaning robot.[86] (R) B1.[79] (S) MEISTeR.[79] (T) Survey Runner.[79] (U) Telescopic robot.[79] (V) Lake Fischer.[79] (W) PMORPH.[79]

before failure. Given the nature of radiation-induced failures, a solution that maximizes the useful time available to a system is the key factor in determining success. The maximum radiation level measured in Fukushima Daiichi Unit 2 Reactor is 530 grays (Gy) h^{-1}.[1] As shown in Figure 1, most of these systems have an effective mission time of 0.2–1.9 h before failure. One of the most challenging aspects of this environment is the near-constant informational and physical uncertainty associated with the highly unstructured work zone. Although robotic systems might be capable of performing essential tasks in these environments, they will likely end up using most of their time for tasks such as localization, mapping, and navigation.

The current approach to operating in these harsh environments is to deploy ever more complex, innovative, and expensive field robotics, which are often in the form of single units that can perform a myriad of functions to provide the necessary capability. The trend of single robotic systems has had limited success and appears to be approaching operational requirements that cannot be achieved, particularly in environments such as the ones presented by Fukushima. From a total system perspective, the potential for parallel redundancy is severely limited by the singular failure potential of one or a handful of field robots.

Each robot also faces the same problem each time it enters the environment: Each field robot will have to perform simulataneous localisation and mapping (SLAM) and obstacle avoidance and crucially each has a similar effective working time, driven by its TID. This is because the current protective measures that can be applied to electronics in radioactive environments can only provide so much time. The electronics cannot be upgraded further and from a mission completion perspective, deploying successive field robots does not necessarily increase the progress of the intended mission. There is a pressing need for the current technologies available to industry to be utilized in such a way that they can address the operational requirements posed by environments such as Fukushima.

A promising answer to these problems is the deployment of modular and multirobot systems. They have some key benefits that are well placed to answer such problems: They are inherently redundant and often one of the guiding design principles of modular robotics is to maximize the parallel redundancy in the system. Stemming from the same principle, these systems are often relatively cheap per individual unit, benefiting from the emergent capability of a system of comparatively simple units.

Although modular robotic systems do have significant potential, there are still significant barriers to their widespread adoption in industry, particularly the nuclear decommissioning industry. Practically, modular robotic systems have not yet been built at a physical scale that provides any useful work in such environments. Nuclear decommissioning tasks tend toward heavy engineering and so require significant force and power requirements. Next, the problem of system control is unavoidable and grows as the size of the system grows. The need for precise and explainable control in the system autonomy architecture is of paramount importance when operating on critical infrastructure where mistakes will have detrimental effects that last for thousands of years. Modular robotics also face the major problem of TID, exactly as field robotics do. In this way, it is the major limiting factor that renders any system design principle, innovative control system, or specialist capability irrelevant as the hard limit imposed by radiation on the current hardware protection capabilities available.

The question becomes, given the present need to operate in such environments and the limiting factor of radiation hardening, what is the best approach to maximize the available operational time in an environment within current capabilities? This work will present a survey of current solutions for the nuclear decommissioning sector and the current state of the art in modular robotics. We will then present Connect-R, a modular robotic system that is designed to answer the question posed before, as a potential solution to the urgent industrial need for robotic solutions in the harshest environments.

2. Robotics for Extreme Environments

The use of robots in extreme environments removes the requirement for people to operate in such dangerous environments, which reduces the risk to human lives, reduces the cost of operation in these environments, and helps increase productivity. The requirements for robotic systems vary with the different domains they are deployed in and examples of this variation can be seen in current robots designed for extreme environments such as deep sea operations, mapping the sea bed, space exploration, offshore environment monitoring, as well as nuclear maintenance and decommissioning.

The offshore environment is an extreme environment that can benefit from the use of robotic platforms. The international offshore energy industry currently faces the challenges of a fluctuating oil price, significant and expensive decommissioning commitments for old infrastructure (especially in the North Sea), and small margins on the traded commodity price per kilowatt-hour of offshore renewable energy.[2]

There have been several reported accidents and explosions of offshore rigs, with the most widely reported and studied tragedy being the Deep Horizon oil spill in the Gulf of Mexico.[3] The sensitivity of the product from offshore oil and gas platforms and the harshness of the environment leads to critical health and safety challenges. Thus, continuous inspection and monitoring of offshore facilities is a vital task and requires technologies to prevent accidents and ensure the safety of human and marine life.

Operators are seeking more cost-effective and safer methods for inspection, repair, and maintenance of their topside and marine offshore infrastructure. Robots are seen as key enablers in this regard to improve health, safety, and environment, and increase production and cost efficiency. Robots can be deployed in the air, on the rig, or in the subsea.

Nuclear environments also present significant risk to human lives due to the radioactive nature of these environments. The nuclear energy sector provides multiple use cases where robotics is critical for success during the operating lifetime of the reactor. Nuclear fission plants have a long history of using electromechanical and robotic solutions for inspection, refueling, and maintenance. Research into nuclear fusion has also relied heavily on robotics in the last 30 years,[4] and once ready for use generating energy, the fusion sector will be entirely dependent on robotic remote maintenance solutions due to the high radiation levels completely precluding human access to many facilities.[5,6]

The multitude of legacy nuclear installations that exist around the world also provide a formidable challenge in terms of their decommissioning, with the UK legacy nuclear facilities alone projected to take over 100 years to fully decommission, costing between £100 and 200 billion without major technological improvements.[7]

Nuclear decommissioning, however, is still an essential task due to the many health risks associated with nuclear assets around the world. Nuclear environments present many challenges, including hazardous working environments requiring protective equipment and radiation hardening of electronics; limited time windows for operation; limited lifetime for electronics; limited access through which to deploy the systems; unstable structures present that prevent occupation; lifting of heavy objects (≈50 kg) that require mechanical assistance; processing of large volumes of liquids (thousands of liters). Therefore, robots are vital for nuclear environments as it is impossible to have operations conducted by humans in these environments. There have been several robotic systems developed in the past for different nuclear zones around the world.

Following the accident at Three Mile Island in 1979, different mobile robotic platforms for inspection, decontamination, and dismantling of the three mile Island reactor-2 (TMI-2) zone have been developed. Gelhaus and Roman[8] developed the "ROVER" (remote reconnaissance vehicle, RRV), which was a remotely operated multitool vehicle with six wheels. The robot was capable of conducting environmental monitoring tasks, video transmissions, sampling, cleaning, and decontaminating areas of the nuclear zone. LOUIE I[9] is a small lightweight surveying robot developed to take radiation measurement of areas that other robots cannot physically reach in the TMI-2 zone. There are other examples of nuclear robotic systems that were developed for the Chernobyl zone after the accident in 1986. Potemkin et al.[10] developed "KLAN," which was utilized for dosimetric reconnaissance, decontamination, and rubble clearing in the Chernobyl zone. The "Pioneer" robot was developed to assess the structural integrity of the sarcophagus in the Chernobyl power plant and generate a 3D map of the nuclear zone.[11–13] The "JAEA-3" robot[14] was developed for the Fukushima Daiichi zone, where the robot can take gamma-ray imaging on various floors of the reactor buildings. The "Quince" robot was developed by Nagatani et al.[15] for the Fukushima Faiichi zone and was used for surveillance missions, to explore the inside and outside of the reactor buildings, to perform dose measurements, and to sample contaminated water. Tsitsimpelis et al.[16] provide an extensive literature review of past and current ground-based robotic systems developed for the characterization of a range of different nuclear environments and zones.

Research has been conducted to remove electronics from robotic control systems through the use of soft robots and fluid logic. Mahon et al.[17] used the design principles of digital electronics and demonstrated an integrated fluidic circuit with fully integrated fluidic switches and actuators. Fisher et al. highlighted the requirement and benefits of robots in extreme environments in their review paper.[18] Irawan et al.[19] reviewed the methods of contruction for reconfigurable modular swarm robotics can be used in situ for autonomous 3D printing in extreme environments.

3. Robotics in Industrial Applications

In proposing a pragmatic approach to industrial-scale deployment of robotic systems, this section will look at the current state of robotic systems that are widely deployed in industrial settings. Many robotic systems found applications in assembly lines and industrial handling, including processes such as transporting, palletizing, grasping, packaging, and picking. Chen et al.[20] developed a smart companion robot for the automotive assembly industry to assist human workers in lifting, transporting, and manipulating heavy payloads such as batteries and car body parts. Unhelkar et al.[21] designed a mobile robot system capable of operating on the moving floors of automotive assembly lines. The purpose-placed dynamic floors play an integral part in the robot's state estimation and path planning for task completion. Reid et al.[22] filed a patent for an automated assembly manufacturing involving robotic arms for all assembly applications in industrial manufacturing. Bischoff et al.[23] demonstrated latest trends in the KUKA Lightweight Robot, showcasing its novel features and demonstrating different applications for the robot. Haddadin et al.[24] demonstrated advanced algorithms for role allocation in human–robot collaborative industrial assembly and safety replanning. This system was commercialized by KUKA robot. Sabattini et al.[25] developed an autonomous guiding vehicle as part of the plug and navigate robots project, for industrial logistics. The robot differs from other autonomous guiding vehicles in that it is designed to operate in environments shared with human operators, utilizing advanced sensing capabilities.[25]

Computer numerically controlled (CNC) machine tool tending is another popular industrial handling application that is aided by robotic solutions. Vosniakos et al.[26] developed a task-oriented offline parametric programming technique for a six-axis industrial robot that tends to CNC lathes. Wang and Hirai[27] developed a soft gripper for food handling and lunchbox packaging on a mass scale. Using the compliance of soft materials, the gripper can overcome a wide range of uncertainties such as size, material, and shape. Conversely, Dyrstad et al.[28] used a dual-resolution convolutional neural network to enable bin picking of reflective steel parts by a six-axis robot.

Robotic systems have also found other applications in industry, including cleaning, welding, and painting. Regular cleaning requirements in food, pharma, and semiconductor industries make robots a very useful tool for such applications. Prabakaran et al.[29] developed a Tetris-inspired reconfigurable floor-cleaning robot that solves issues with traditional fixed-morphology systems. The robot can reconfigure its shape to maximize floor coverage in its surrounding environment.[29] Górka et al.[30] demonstrated the use of the KUKA KR180 robot with a welding torch for assistive spot welding of DOCOL 1200M. Hu et al.[30] developed a new legged mobile robot for welding with hexapod mobility and 6 DoF manipulator. The robot can overcome obstacles in its environment and move freely on unstructured terrains.[31] Asadi et al.[32] developed Pictobot, which is a cooperative robot for interior painting of industrial developments.

4. Modular Robotic Systems

Field robots performing tasks in unstructured environments need to adapt to variable constraints in their environment. Many robots to date have provided a single unique solution to a specific real-world application, but they are usually hard to use and adapt for other applications.[33] Due to the rigid nature of conventional robot design, conventional robots do not cope well with changes in their environment. Their repair and maintenance are also costly and generally require trained personnel.[33] In contrast, modular robots (or assemblies of modular units) make it easier to repair the system, to replace modules, and to control the robot, which gives the robot more robustness and capability for achieving new tasks in unstructured environments. Modular robots differ from traditional robots in that their entire body is based on a collective of individual submodules. A robotic module is defined as a unit that performs typical tasks of a robot, either fully or partially, and has the ability of interacting with other units or modules to create a system with new capabilities. Modular robotic systems have attracted major interest over the past years.[34–45] The interest in modular systems is due to the hypothesis that a single advanced robot is more expensive and less robust than multiple low-cost modules.[33,46,47] The ability to adapt to unknown environments makes modular robotic systems very versatile as they can be easily reconfigured for different tasks.[33,34,39,46,48–50]

Modular robots that are able to automatically transform their size and/or shape to meet specific tasks or environments are referred to as "self-configurable" robots. Modular self-reconfigurable robots (MSRRs) are particularly versatile, with many degrees of freedom. An MSRR is able to repeatedly transform its morphology and/or size by connection and disconnection of its constituent modules,[51] which allows the optimum configuration for specific tasks to be achieved. MSRRs, unlike modular robotic designs, are able to change their morphology with minimum human involvement.[33] In unknown or challenging environments, this capability is particularly advantageous as a robotic system with fixed morphology would not have the same level of adaptability to manage a complex or unknown environment.[51,52] The interchangeable capability of a modular system allows for self-repair, making the system robust as defective modules can be separated from the system and then replaced. This set of advantages makes self-configurable robotic systems ideal for deployment in extreme environments.

The first known concept of reconfigurable modular robots was suggested by John Von Neumann[53] in the 1960s, where he proposed the idea of adaptable universal robots. The Polybot by Yim et al.[40] was the first modular robotic system to demonstrate two sequential topologically distinct movements by self-reconfiguration.[40] In 1996, the Tetrobot was designed for applications in extreme environments such as mining, space, and undersea.[54] It uses concentric multilink spherical (CMS) joints to allow several struts to connect while sharing a central point of rotation. Another example of a modular robotic system is the Self-assembling Modular Robot for Extreme Shape-shifting (SMORES), which was designed to be polymorphic, metaphoric, and inexpensive, with an aim to improving the versatility of self-reconfigurable systems.[55,56] By being simplistic in its construction, Alice is another modular robot that is low cost, small in size, and power efficient, and is designed to improve the autonomy of modular robotic systems.[57] Superbot,[42] designed for NASA space exploration, was constructed for accomplishing complicated tasks in unknown, harsh environments.

Modular robots can be designed to assemble into discrete cellular structures, such as the work conducted by Jenett et al.[58], where cuboctahedral unit cells are used to created structures through the use of magnets and build a modular robot. The space

Table 1. Classification of modular robotic systems according to form factor.

Category	Scale
Micro	$0 < x < 1$ mm
Mini	1 mm $< x <$ 5 cm
Macro	5 cm $< x <$ 1 m
Mega	1 m $< x$

sector is another area where modular robotics research is popular, where the goal is to provide structure in the extreme environment of space. Torisaka et al. designed an electromagnet-based self-assembly system for modular space structures.[59] The University of Houston and MIT have collaborated with NASA to create ARMADAS.[60] The morphology of a re-configurable system is important as it is necessary to have a structure that suits the mission. Moreno et al.[61] designed a module, EMERGE, that can be built and reconfigured quickly and easily to conduct research of entirely autonomous morphology evolution in full cycle reconfigurable hardware of various topologies. Re-configurable modular robots can come in many different forms. Usevitch et al.[62] designed an untethered isoperimetric soft robot that is made from several pressurized tubes.

The current trend in modular robotics is to make robots small, but that limits their usefulness in real-world applications. **Table 1** classifies modular robotic systems according to form factor. "Microrobotics" describes robots with dimensions ranging from a fraction of a millimeter to 1 mm. "Minirobotics" describes robots having a size range between a millimeter and 5 cm. "Macrorobotics" describes systems with dimensions between 5 cm and 1 m. "Megarobotics" describes systems that have a size larger than 1 m. Many researchers develop designs in micro- to macrosizes for addressing various scenarios in MSRRs. The form factor is chosen at a trade-off between system capabilities and environmental requirements. Examples of modular robotic systems in each of the form categories include: Micro (Catom,[63] MEMS microrobot,[64] Omnidirectional walking microbot,[65] Walking silicon microrobot[66]); Mini (Robot Pebbles,[44] M-blocks,[36] Claytronics,[67] Slimebot[68]); Macro (Polybot,[40] Superbot,[42] CoSMO,[69] Particle robot[34]).

5. Task Planning for Extreme Environments

Task planning is a critical part of any robotic system that aims to operate in critical environments, and due to the verification and accountability requirements of operating in a critical infrastructure, most control and planning systems are heavily reliant on human input. The M-Blocks system developed by Romanishin et al.[36] combines magnetic robots to create cubic structures. The focus of this work is on the hardware. Stewart and Russell[70] presented a distributed feedback mechanism to construct a "wall" via individual robot agents. Jennett et al.[71] proposed an MRS that constructs a 3D structure by carrying building blocks and arranging them. The authors used local control rules based on the neighboring environment. With the strict criteria of explainable AI, autonomous decision-making structures such as task planning for similar scaled problems are relatively few. Dutta et al. present a decentralized algorithm for self-assembly based on subgraph isomorphism; this work is intended for an unknown initial state of each robotic agent that would be unsuitable for extreme-environment scenarios.[72] Tucci et al. present a decentralized self-assembly algorithm based around the abstract of a catom,[73] a virtual voxel that can be occupied or unoccupied. This is an effective algorithm but untested on real robots with more complex connection criteria.

The RoboCup Rescue Virtual Robot Simulation provides a common virtual environment for researchers working on urban search and rescue. In this simulation, a devastated area needs to be explored by a team of robots to find survivors. Our focus is to create a structure to facilitate other robotic systems to work in inaccessible areas, for example, a reactor, instead of a whole town. There are clear parallels on both scenarios, for example, data gathering, robot cooperation, and centralized versus distributed controls. The RoboCup Robot League was set up to increase awareness of the challenges involved in search and rescue applications. It requires robots to search for simulated victims in unstructured environments.

The biggest challenge for conventional planning is working in noisy environments. This requires effective data gathering, keeping a human in the loop, and replanning when necessary. First, symbolic planners see the world in terms of symbolic relationships; for example, a module is at location x,y,z. The data provided by the module sensors are translated into a planning domain definition language (PDDL) problem, which symbolic planners can then solve. Later in this study we present a visualization system that allows a human operator to visualize and give the go ahead for each step in the solution plan provided by the planner. If replanning is necessary, for example, exogenous events, the human operator can easily modify the goal or the current state in the PDDL language to adapt to changing circumstances.

6. The Connect-R Modular Robotic System

As mentioned in the introduction, the Connect-R system aims to answer the question of how to maximize the time available in a target environment with a modular robotic system. The electrohydraulic system also demonstrates an approach to nullify the problems of developing an industrial modular robotic system, namely, scale and control. Here, we present the Connect-R in terms of its operational principle, physical design, control strategy, and intended usage.

The Connect-R project is a flagship project funded by Innovate UK. The partnership between industry (Barrnon, Ross Robotics, Tharsus, Jigsaw Structures), academia (The University of Edinburgh and Royal Holloway University of London), and government research and development (RACE) provides an excellent opportunity to disrupt the current space.

6.1. Providing Structure in Unstructured Environments

Providing structure in unstructured environments is the design principle by which the system of the Connect-R is designed. In direct answer to the question presented (how to maximize the effective working time in a nuclear environment?), Connect-R provides both a physical and informational structure. The modular robotic system is deployed to self-assemble into a cubic structure that other individual robots can leverage as a simplified environment in their efforts to perform useful tasks. This structure not only acts as a uniform environment where a standard and discrete form of locomotion can be utilized, it also doubles as a constant map of the environment. These two features are crucial in reducing the uncertainty that leaves single field robots spending most of their time on SLAM and obstacle avoidance in the environments. The robotic structure also provides an informational infrastructure that can be used for key points of feedback, such as providing state estimation and indicators of successful movement between points in the environment.

Regarding the hard limit posed by TID, although the electronics of the individual robots of the Connect-R system are not more resilient to radiation hardening than other robotic solutions, Connect-R is able to make use of its failure for the next robots that are entered into the system. By focusing its useful time in the environment on self-assembling into a structure, it will remain in a useful structure due to its hydraulic-driven actuators.

Providing *structure in unstructured environments* is the key point in this approach, in contrast to innovating increasingly complex individual robots that attempt to mitigate uncertainty presented by unstructured environments. This work advocates that comparatively simple individual robots can, as a system, offer a better solution when focused on reducing the target environment to a state that is manageable by the current technologies available. This approach advocates that the technological gap between operational requirements and current robotic capability can be better bridged by deploying a simpler system that provides an advantage to a robot that cannot bridge the gap itself. Instead of deploying ever more complex systems to overcome the environment, the pragmatic approach is to deploy a simpler system that reduces the operational requirements of the environment to meet what is achievable.

6.2. Physical Design

Connect-R is an electrohydraulic robot that is designed to be larger than any other modular robotic system precisely so that it can operate effectively in industrial environments. It was also designed in tandem with Task Planning to optimize it for the proposed autonomy architecture. Each individual module of our modular robotic system is defined by its capability to move in a 3D space and form orthogonal connections to other identical modules. **Figure 2** shows the possible basic movements of each module of our proposed modular robotic system. Each module can extend, connect to other modules, and rotate around other modules. The module also has a locomotive ability, where it can move on top of other modules. It can move by independently actuating sections of the main body. Using the correct sequence, it can move via an "inchworm"-like motion.

Each module has identical actuating manipulators at each end, which makes the module completely symmetrical. Each manipulator has three degrees of freedom, where the manipulator can be utilized to manipulate either the module itself, or another module connected to it. As the manipulators can only be deployed from the ends of the module, structural connections can only be achieved by maneuvering each module so that the manipulator is free with adequate space to move the robot into positions. This creates a complex set of rules for valid structures and increases the importance of autonomous task planning; however, the physical symmetry and relative simplicity of the manipulator capabilities are intentional such that only a discrete number of actions with well-defined results are possible. This is crucial for the success of the autonomy architecture.

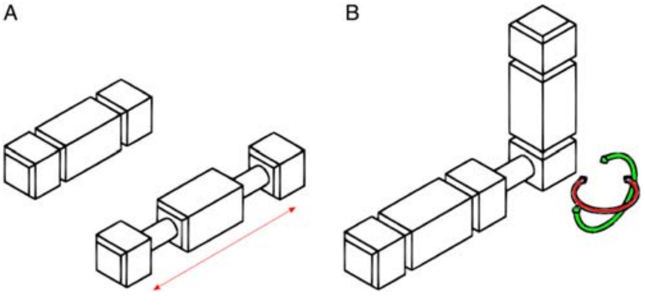

Figure 2. Module configuration as kinematic primitives. A) Demonstration of a key motion primitive that a module must be able to achieve—extension—which allows for translation in the world state. B) Demonstration of the two degrees of freedoms in rotation that a module can apply to a connected module. This is a key motion primitive in the system's ability to build structures.

The electrohydraulic actuation is key to the robot being at a scale that is practically useful; each robot is 1–2 m long, giving the system an opportunity to occupy environments that are orders of magnitude greater than the current state of the art. Programmable logic controllers are used for hydraulics control. Although programmable logic controllers (PLCs) are dated by current standards, they remain the industry standard to operate in nuclear environments and so to enable smooth integration with the standard software frameworks. **Figure 3** shows a robot operating system–programmable logic controller (ROS-PLC) framework to enable inline control that has been developed specifically for Connect-R.

6.3. Task Planning

Autonomy architectures are key to robotic systems and are crucial to ensuring successful system performance. As mentioned previously, in the application of deploying robotic systems to work in extreme environments and critical infrastructure, there are the necessary requirements of accountability and verification in the autonomy structures. These strict constraints usually disqualify model-free machine learning and deep learning techniques due to their data-heavy training periods and an inability to decompose potential failures after training, despite their obvious power and popularity in both the literature and industry. It is important, then, to base the autonomy structure on a system that is model-driven, transparent, and accommodates human integration. This is crucial to the pragmatic approach suggested in this work, exemplified by the Connect-R project's autonomy structure.

In Connect-R, the AI that plans and produces the target structures is Task Planning, currently relying on the FastDownward planner.[74,75] PDDL 2.1 was chosen as the language with which

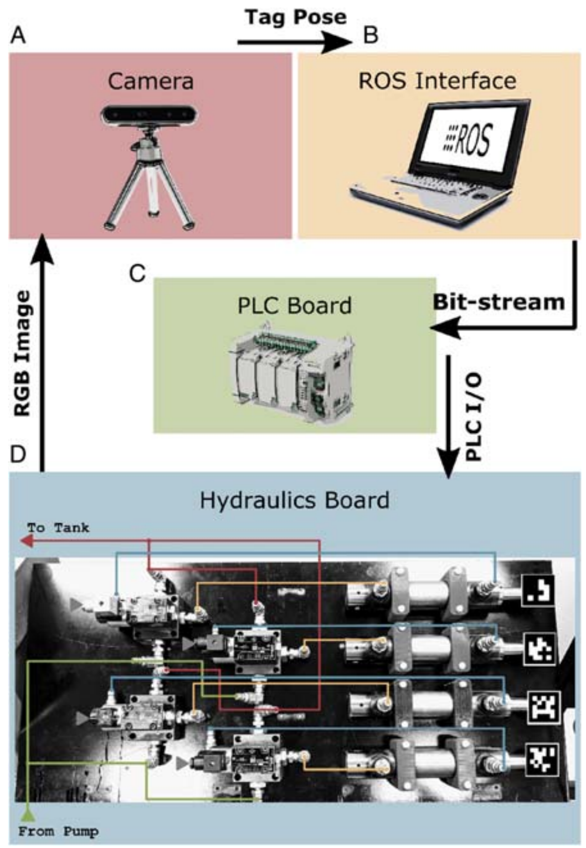

Figure 3. An overview of the ROS-PLC framework. A) A web camera takes an RGB image from the hydraulic board and passes the tag pose to the ROS interface. B) The ROS interface uses the tag pose to determine the next operation, communicating this operation to the PLC board via a bit stream. C) The PLC board interprets the bit stream from the ROS and addresses the contacts for the solenoid valves on the hydraulic board. D) The solenoid valves engage, and the hydraulic fluid flows to the hydraulic cylinder, moving the tags affixed to the ends of the cylinders.

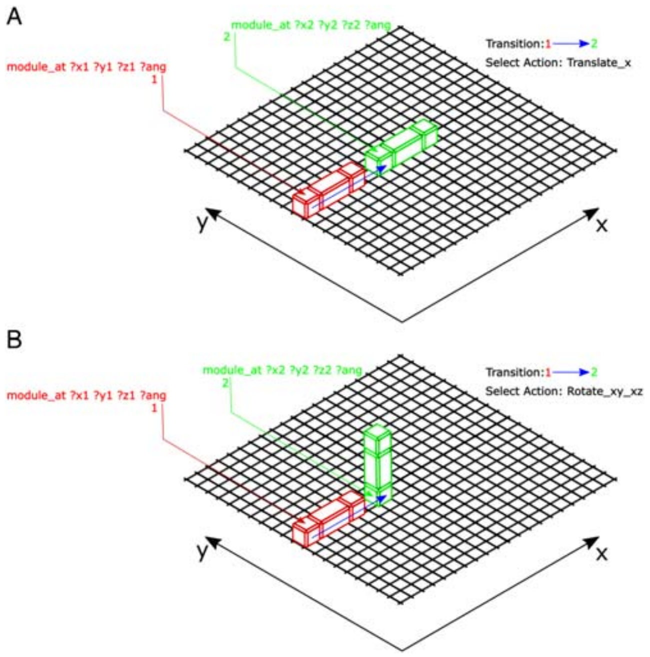

Figure 4. Representation of Task Planning. A) A graphical explanation of the action selection in Task Planning to transition between two states without a change in orientation. B) A graphical explanation of the action selection in Task Planning to transition between the same to coordinate states, but with change in module orientation also.

to represent the world state of the target environment through the planning domains. PDDL allows for a flexible goal state that can be fully specified, for example, from setting all robots to specific positions and orientations to being as vague as simply requesting that a certain position(s) be occupied by one part of the Connect-R system.

To aid in human interpretation so that they can be an effective part of the autonomy structure, the world state is defined by coordinates and robots, for example, a vector-based representation to signify that a robot is in a specific location with the predicate (robot-at ?x ?y ?z ?orientation). PDDL uses "actions" to model the world dynamics: modeling the valid transitions of objects inside the world state; for example, (translate_x ?x) will translate a robot in the x dimension of the world state.

Figure 4 shows a graphical explanation of this system. The coordinates of the world state are denoted by the grid space, with the corresponding dimensions. On the left, it can be seen that to transition a robot from state 1 to state 2 (?x1,?y1,?z1 to ?x2,?y2,?z2), the planner selects the action "Translate_x"; similarly the right shows that to transition with a change of angle then the planner will choose "Rotate_xy_xz." These examples were chosen relative to Figure 4 as they demonstrate how the key kinematic primitives of each module are represented in Task Planning. Changes are easily incorporated by nonplanning experts by simply adding, removing, or modifying the existing PDDL predicates in the domain file and this can be done while keeping backward compatibility with previous scenarios (PDDL problem files).

Depending on the complexity of the requested task and the available time it might not be practical to guarantee a solution optimum. The Connect-R AI is compatible with both optimal and suboptimal state-of-the-art planners. Note that although the planner solutions are calculated without human input, we can bias the planner preferences by giving different costs to different actions; for example, if the priority is to lengthen the life of the struts, we can make it more expensive to put the struts in hazardous environments, e.g., higher radioactivity levels. The planner will try to find the cheaper solution; that is, cost is calculated by aggregating all the action costs in the final plan from the initial state to the goal state. The more expensive an action is, the less frequently it will be used unless it is unavoidable to achieve a goal state.

Practically, humans interact with the AI structure by ensuring plan execution can be stopped at any time. Sensors map the current state of the world into a PDDL state. If new restrictions need to be added, this can be done by simply using the latest snapshot of the environment and modifying the goals as desired.

7. Discussion

Robotic systems for nuclear environments were being developed since the 1960s, but it is only recently that the most significant technological advances in those systems have taken place and allowed them to perform better in such environments.[16] In 2012, Kawatsuma et al.[14] provided a study on emergency response robots following the first year of the accident at Fukushima Daiichi in 2011. The study reports that most of the robots developed and deployed after the accident either were not fit for undertaking missions due to physical constraints and lack of maintenance, or major modifications were required for the robots before they could be successfully deployed in that nuclear zone.[14] Advances in computing performance and improvement in the radiation resistance of electrical and mechanical components (development of new materials that can withstand higher radiation levels) has increased the reliability of robotic systems for nuclear environments. However, a major challenge still remains for robotic systems in nuclear environments, which is the informational and physical uncertainty associated with the highly unstructured nuclear zone. Although robotic systems might be advanced enough to conduct essential tasks in these environments (such as sludge removal, deploying sensors, inspecting valves, sampling, and manipulation of payloads), accessing the target area is mainly limited, and most robotic systems fail before reaching their required area or are unable to navigate to that area due to the unstructured nature of the environment.

Connect-R is proposed as a system with significant contributions to the operational requirements of nuclear decommissioning, driven by a larger contribution which is to frame the approach to such environments from a different perspective. In surveying the literature, it was found that a modular robotic system at a useful scale was lacking and would be a major step forward in providing operational capability in these nuclear environments. Connect-R is an electrohydraulic robotic system with individual units of length 1–2 m. This is a major contribution as now Connect-R can actually affect change at an industrial scale at such sizes; see **Figure 5** for a comparison of actuation mediums and the power-to-weight ratio that they can develop. In adopting electrohydraulics, Connect-R has also contributed an ROS-PLC module that allows for control of PLCs. This is an important step in the pragmatic application of technologies because although PLCs are dated, they are an industry standard in those environments and are a good example of working with existing technology instead of innovating over the verified hardware. The next major contribution from Connect-R is the autonomy structure. The Task Planning system has been specifically designed to include a human operator and as such is a significantly more explainable system than other model-free techniques. The design constraints of Task Planning have been reflected in the physical robot, allowing for a scalable, accurate, and deterministic autonomy model of the system, which can be easily interpreted by the human operator. The physical symmetries in the robot design have allowed for this feature.

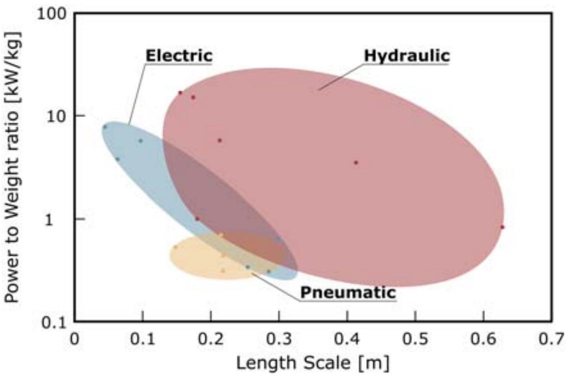

Figure 5. Robots and machines use electric-, pneumatic-, and hydraulic-type actuators for various applications. This graph shows the power-to-weight ratio versus length scale of the actuator and a metric for comparing these actuators.

Perhaps the most important contribution is how the Connect-R system addresses the unavoidable failures imposed by TIDs. The literature review demonstrates that the prevailing approach to operating in these environments is to innovate and further raise the technological level of the operating robots to meet the demands of the environment. It has been shown though that the uncertainties that nuclear environments pose cause failures regardless of the technological capabilities. This is mostly due to the time required for a robot to actually reach an area to do work, so time essentially wasted performing SLAM and obstacle avoidance routines. It is also clear that capabilities in these environments are needed today, and so solutions that work today are needed. Connect-R demonstrates that if the problem is viewed from the perspective of reducing the environment complexity to a level that is manageable with current technologies, the time spent in the environment can be maximized and useful work achieved before TIDs are encountered. Connect-R self-assembles into a physical structure that acts as a simplified environment for mapping and obstacle avoidance purposes and in so doing also offers known hardware to provide important feedback for tasks such as state estimation. Connect-R *provides structure in unstructured environments*, which is also to say that it provides a new structured environment where others can flourish. **Figure 6** shows how Connect-R is intended to be deployed in target environments, in this case to access higher stories in an urban environment.

8. Conclusion

The call for effective and robust automation is growing and its need is becoming ever more urgent as we approach a critical time in the life cycle of many of our core industries. Couple these aging structures with the general push to become more competitive and efficient through automation, and the need to deploy robotic solutions is an immediate concern.

This study presents a survey of current robotic systems that could be deployed for critical industry services, particularly in extreme environments and, in contrast, presents the case for a new approach to the requirements of these tasks, exemplified by the Connect-R system. The Connect-R system is a self-assembling robotic structure designed to be a practical and robust step in the direction of deployed, real-world systems. Its defining purpose is to provide *structure in unstructured environments*, and it achieves this on two levels. First, it self-assembles

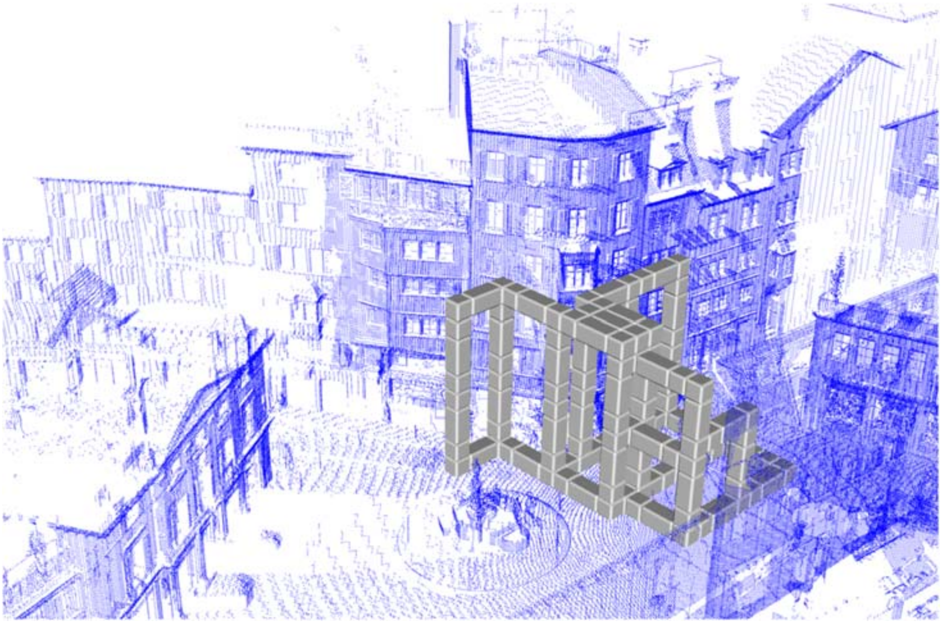

Figure 6. Connect-R system vision: demonstrates the vision for how the Connect-R system will be deployed. The point cloud representation shows a city landscape and a structure of identical modules is built up in the environment. It can be seen that this structure could be attempting to provide access to the higher floors of the tallest house in the point cloud.

into a physical structure for other robotic systems to use to access the environment. This feature is particularly useful in disaster zones or otherwise inaccessible areas for humans to access. Second, the uniformity of the structure it can become provides an inherent structure and certainty for other robotic systems to exploit. The risks and uncertainty surrounding accurate state estimation, SLAM, and motion planning are mitigated by the safety of a repeating, discrete structure that was purposefully placed, in an otherwise uncertain environment, for a robotic system to use as a resource.

This study demonstrates that by following the approach of providing *structure in unstructured environments*, the present need to operate in these areas can be better realized on a pragmatic timescale by deploying relatively simple robotic units that when combined can effectively change the environment to a technical difficulty that is more approachable to current capabilities. This would constitute a major change in the standard trajectory in solving these problems, which usually works to innovate the current technologies to successfully operate in the original environmental conditions.

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Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

M.E.S. and J.O.R.—writing and editing the manuscript, lead authors of the work; K.D., S.T.M., F.I., B.L., and S.F.A.—writing sections of the manuscript; G.M., E.T.J., M.P.N., and S.B.—reviewing the manuscript; A.A.S.—lead advisor and primary editor of the manuscript.

Keywords

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