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Towards wireless communication in control systems of the civil nuclear energy sector☆

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ABSTRACT

The use of wireless communication within the civil nuclear industry can bring many benefits over wired solutions, such as reducing lifecycle costs and enabling new applications in asset and process management. This paper will discuss aspects of wireless communication in industrial control systems, i.e. termed wireless control systems, of the civil nuclear industry. In this respect, we will review previous use of wireless communication in the nuclear industry, and provide the results of a recent feasibility study of wireless communication for an industrial, civil nuclear control system. The studied use case was of an advanced nuclear modular reactor, the Stable Salt Reactor (SSR), and the augmentation of one of its control systems, the refuelling control system, with wireless communication. Hence, in contrast to previous work on wireless control systems, this paper here will focus on the complex and rigorous processes required for regulated safety which have to be followed to allow for wireless control to be implemented in the nuclear civil sector. The following analysis and design procedure was followed: (a) the decision process for choosing the refuelling control system, (b) the review for a suitable communication protocol and technology, the analysis for placement of wireless transceivers for sensors and actuators, (c) the analysis for wireless communication integrity, (d) the basic analysis and guidelines for control system robustness under packet loss, (e) the discussion of possible self-powering options and (f) the safety analysis of the control system under communication failure. Our initial hypothesis is that wireless control systems in Nuclear Applications can improve asset integrity. Control systems can be made more robust and secure to external influences by securely communicating control responses and asset information within a Nuclear Plant. Safety is also improved by reducing the number of operator interactions required for servicing connections, as failures are reduced overall. The removal of power/data harnesses from in-reactor applications can enable faster deployment and replacement of instrumentation for new builds, existing plants and decommissioning.

1. Introduction

Controlled nuclear reactions have been used to produce electricity since the 1950s, contributing a large proportion of the world's low-carbon electrical power production and being the largest nuclear civil application to date (Association, 2021). With an average operating life of 40 years, nuclear power plants require continuous maintenance and oversight of complex systems. End of life decommissioning of nuclear power plants is also a complex and costly endeavour. Therefore, innovations that reduce cost whilst maintaining operational performance and safety are of great value to the industry.

An ever-present cost in both legacy and new builds is the one related to wiring for both power delivery and data connectivity for control and monitoring. Any wiring must follow specific technical requirements for both its construction and installation, which is both expensive and difficult to install and maintain. Replacing such wiring with a wireless system within civil nuclear applications may have advantages for newly

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built plants, existing plant upgrades, and for plant decommissioning. As a reference point, general cost reductions could be as high as 50% considering an example implementation of wired Voice-over-Internet Protocol (VoIP) vs. wireless local area network (WLAN) (Fuhr, 2016).

Wireless-based Control and Instrumentation systems (C&I) in the nuclear power industry could not only reduce general costs, but could enable a whole new range of applications. Wireless applications within the nuclear power industry have been restricted to non-reactor applications, such as voice communication services for operators and sensor measurements not linked to the operation of the power plant itself (i.e. systems not relevant to safety), e.g. Energiforsk (2018). Current (C&I) systems could be improved by providing redundant communication channels, making them more robust. The power plant lifecycle would also be improved, as decommissioning times would be shortened due to reducing the number of physical assets (i.e. wired connections vs. transceivers for wireless nodes). Placing more sensors closer to the reactor would allow for better asset management, with more accurate and immediate feedback of the reactor's operational condition informing pre-emptive actions to prevent or reduce the impact of incidents.

The deployment of any control and instrumentation (C&I) software or hardware that can affect the operation and safety of civil power plants is highly regulated. This regulation includes the design and implementation of C&I for closed-loop control systems. Regulatory frameworks are based on the interpretation and application of local and international technical standards by a regulatory body. Such frameworks offer guidance and propose categorizations for different aspects involved in the functioning of civil power plants. For instance, plant safety functions are categorized according to how important they are to safety, from A being the higher, to B and C (BSI Standards Publication, 2010a, 2010b). Increasingly, the regulatory bodies behind the adoption and application of such standards, like the Office for Nuclear Regulation in the UK (ONR) (Office for Nuclear Regulation U.K., 2020) use a goal-oriented approach to regulation. The goal-based system creates an opportunity for new technology to be adopted, provided sufficient evidence is available to demonstrate that technical and safety related goals have been met. Special considerations are given to wireless technologies, as it potentially brings challenges such as cybersecurity and Radio Frequency Interference (RFI), with reported cases of the latter in the form of false alarms and faulty performance of legacy equipment in nuclear power plants (Ko & Lee, 2013). A more in-depth discussion of the regulatory challenges behind implementing solutions such as the one discussed in this paper will be done in Section 3.2.

This paper provides an overview of the technical and safety challenges for designing a wireless control system to be used in a civil nuclear application. We completed a feasibility study to propose a possible solution for a wireless control communications and energy scavenging system for the C&I function with IEC61513 Safety Category C (World Nuclear Association et al., 2015) Gantry Refuelling System on a Stable Salt Reactor (SSR) (ICON, 2018). The safety and regulatory aspects of our particular use case are discussed, providing a technical case for its adoption and the initial considerations for a safety claim. This will act as an example for a wider discussion about introducing wireless communication into closed-loop control systems for civil nuclear systems.

The rest of the paper is divided into the following sections: Section 2 provides a short overview of key work in the area of networked and wireless control to provide a technical starting point for the wireless control systems considered here. Section 3 introduces the general regulatory and technological landscape of wireless control in nuclear. Section 4 describes the Moltex SSR-W Gen IV Small Modular Reactor and its refuelling system, as a central part of the feasibility study for control in wireless systems. Section 5 describes the technical feasibility study to implement wireless communications and control for the selected use case. Section 6 describes the methodology followed to create an initial safety assessment. Section 7 lists our conclusions and talks about future work.

2. Networked and wireless communication systems for closed-loop control

Networked control systems can, in general, determine two topics: *Control Of Networks* and *Control Over Networks*. The work presented here sits within the realm of *Control Over Networks*. Given the opportunities for communication networks for control, i.e. Control Over Networks, this problem has been researched for more than two decades and accordingly there is comprehensive insight into this topic, e.g. Ge, Yang, and Han (2017), Longo, Su, Herrmann, and Barber (2013), Tipsuwan and Chow (2003) and Zhang et al. (2019), where specifically more recent research and relevant overviews (Ahlén et al., 2019; Park, Ergen, Fischione, Lu, & Johansson, 2018) address the step towards the wireless and industrial domain. Therefore, we will focus on the existing overview literature to allow the reader to gain access to the existing work on Control Over Networks, which is important to introduce Control over Wireless Networks.

2.1. Control over networks

It is vital to acknowledge that since the beginnings of work on Control Over Networks or Networked Control Systems (NCS) (Bemporad, Heemels, Johansson, et al., 2010; Zhang et al., 2019; Zou, Wang, Hu, Liu, & Liu, 2021), the control communication network has not been regarded as a pure random component, while communicating control signal or sensor information. *Control Over Networks* research has for many years widely adopted two different approaches, time-triggered and event-triggered approaches (Ge et al., 2017; Tipsuwan & Chow, 2003; Zhang et al., 2019; Zou et al., 2021); this has been to take advantage of the possible determinism in communication networks, while transmission jitter, data, and communication loss or packet dropouts partially required stochastic and robust models of delay (Liu, Selivanov, & Fridman, 2019) or stochastic sampling to allow for a comprehensive theory of networked control.

Event-triggered and non-uniform sampling control (Ge, Han, Ding, Wang, & Zhang, 2020; Zhang, Han, Ge, Ning, & Zhang, 2023; Zou et al., 2021) has initially focused on stability and therefore on principles such as the 'maximum achievable transfer interval' but advanced to performance and energy oriented approaches. These methods lend themselves nicely to fault-detection, energy consumption minimization while retaining performance across a networked control system. Technologically, contention-based network communication might lend itself towards event-trigged control systems, for which it is necessary that such Carrier-Sense Multiple Access (CSMA) based approaches minimize the delay due to network contention (Ishak, Herrmann, & Pearson, 2016) and provide data-arrival guarantees.

The complexity of control communication networks demands also the co-design of the network and the control system (Ahlén et al., 2019; Park et al., 2018; Zhang et al., 2019). Specifically, the authors of this paper argue that current industrial (legacy influenced) settings may require for the foreseeable future a time-triggered approach for closed-loop control (given the emphasis on deterministic and time-triggered wireless networks in International Atomic Energy Agency (2020)); in this respect, the authors' work (Longo et al., 2013) is a basis for robust and optimal design of controllers (H_2 and H_∞) suited to a complex, yet fixed communication network, either established in advance or to be designed in a constrained optimization framework (i.e. constraints towards communication structure). Here, both bus-based or complex network systems allow for Time Division Multiple Access, i.e. temporally planned scheduling of sensor and control information across the network.

In addition to the current challenges in network co-design (i.e., *Control Of Networks* and *Control Over Networks*), event-triggered control and network stability under constraints (Kim, Park, & Lu, 2022; Zhang et al., 2019), there are challenges around security and privacy (Sandberg, Gupta, & Johansson, 2022). Methods to achieve cyber-security in a networked control system (Ding, Han, Ge, & Wang, 2020; Kim et al., 2022; Sandberg et al., 2022; Yaacoub et al., 2020) are traditionally based on a model-based understanding using estimator methods for anomaly or fault detection, while learning-based approaches have shown to be, for instance, advantageous for multiple, simultaneous attacks. Besides approaches (Yaacoub et al., 2020) that focus on protocol and operational improvements such as continuous monitoring, use of cryptography, and management of data and access privileges through its lifecycle, ensuring security and privacy of networked control systems is still an open challenge.

2.2. Wireless control over networks—In academia and industry

In the realm of wireless networks, the use of spatially distributed, networked sensors, actuators and controllers is often referred to as a Wireless Networked Control System (WNCS) (Park et al., 2018). Such systems (Ahlén et al., 2019; Jia, 2021; Park et al., 2018) have their basis in the general work on networked control systems. This results again in the principal division into time and event-triggered systems (Ahlén et al., 2019; Park et al., 2018) and into the principal requirement for security (Jia, 2021) based on estimation approaches.

WNCSs share similar research topics and challenges as Networked Control Systems, mainly the ideas around co-design, protocols for scheduling and event-driven control, among others. In addition, the use of model-free schemes leveraging techniques from the machine learning literature, such as neural networks and reinforcement learning. This has been done in different applications, from improving the scheduling mechanisms of the network of remote state estimation applications (Chen et al., 2024; Leong, Ramaswamy, Quevedo, Karl, & Shi, 2020), to co-design for improved performance based on sensor metadata (Zhao, Liu, Quevedo, Li, & Vucetic, 2023) or performance metrics derived from semantic understanding of the control application (Chen, Liu, Quevedo, Li, & Vucetic, 2023).

Technologically, the possible complexity and the actual choice of technology for the wireless communication network is a central point (Ahlén et al., 2019; Park et al., 2018), while the popularity of IEEE 802.15.4e wireless communication for control and the inbuilt determinism has clear technological advantages (Scanzio et al., 2020; Thubert, Watteyne, Palattella, Vilajosana, & Wang, 2013) (as discussed in Section 5) versus many other protocols such as general IEEE 802.15.4 protocols, e.g. Zigbee or (Bertocco, Gamba, Sona, & Vitturi, 2008), or IEEE 802.15.1 based Bluetooth (Baker, 2005; Wang & Jiang, 2016). Deterministic channel hopping and a form of TDMA has been encapsulated in Time Slotted Channel Hopping (TSCH) of IEEE 802.15.4e. This and the capability of mesh-networking, allowing for redundancy, has inspired two industrial networks, ISA 100 (Bailey, 2023) and WirelessHart (FieldComm-Group, 2023; Song et al., 2008) suited to closed-loop control in principle.

The number of cases for wireless closed-loop control are still rather limited (Ahlén et al., 2019), which highlights the need for strong industrial commitment to transition from mainly wired control systems.

This work here provides a detailed discussion, how academia and industry might wish to engage for the implementation of novel technologies, such as wireless control networks, to allow for the realization of their technological, economic and societal benefit.

3. Regulatory and technological aspects of wireless systems for closed-loop control in the nuclear sector

3.1. Wireless communication in civil nuclear systems

There is little doubt that the Civil Nuclear Industry has strategically built up an understanding of the use of wireless communication technology (Ataul & Jin, 2015; Deng et al., 2020; Energiforsk, 2018; Fuhr, 2016; Herrmann, 2018; International Atomic Energy Agency, 2020; Kjesbu, 1997; Ko & Lee, 2013; Yu, Chen, & Luo, 2011) for almost thirty years, given the significant economic benefits as pointed out by Fuhr (2016). More importantly, the International Atomic Energy Agency (International Atomic Energy Agency, 2020) emphasizes the open protocol IEEE 802.15.4e and their industrial counterparts, ISA 100 and WirelessHart, while all use cases for wireless systems remain limited to the use of wireless systems for in-plant operator support (Energiforsk, 2018; Yu et al., 2011) or first tests of wireless sensor networks (Deng et al., 2020). Furthermore, we suggested (Herrmann, 2018) the use of wireless communication in the nuclear sector for wireless control, for which an industrially led feasibility study, jointly conducted with academia, is reported here.

3.2. Regulation of control & instrumentation in nuclear applications

The need to demonstrate adequate levels of safety in the civil nuclear sector plays a large role in the choice of technologies used in them. Although a full description of the treatment of safety in nuclear plants is highly complex and outside the scope of this paper, understanding the regulatory context is important since it controls the potential use of wireless communication technologies.

Energy generation from a nuclear plant must be accompanied by a safety case which supports this use, and any such safety case must be scrutinized and judged satisfactory by a national regulator. The overall case depends on ancillary safety arguments about components, subsystems, and systems in the plant that, when working together, achieve safety. Furthermore, the achieved levels of reliability need to be adequate to reduce the risk of radiation releases to a level acceptable to society. In support of this, international and national standards have grown up around nuclear safety to provide a consensus on how to assure the safety of systems and components, which plays a significant role in the regulatory process. Adherence to an agreed standard is a powerful way to provide support for the claim that a system meets the required level of assurance (i.e., verification and validation (V&V) Nuclear Regulatory Commission, 2013).

Applying nuclear safety standards is a non-trivial task, requiring sector-specific expertise. Although general (cross-sector) safety standards exist, such as IEC61508 (Bell, 2006), these often have sector-specific versions (e.g. specific to nuclear or rail applications). All are highly specialized and detailed documents, regardless of whether they derive from a particular sector or relate to specific technologies (e.g. digital C&I safety in civil nuclear power plants BSI Standards Publication, 2010). Different organizations such as IEC and IEEE have developed standards for particular C&I technologies and aspects of C&I, such as functionality, security and safety. The different standards are not entirely consistent among themselves (e.g. IEC 60880 vs. IEC 61508 Lahtinen, Johansson, Ranta, Harju, & Nevalainen, 2010). Regulators act within an international regulatory context led by the IAEA, but each national regulator can choose to focus on a particular set of standards. A national regulator will align with IAEA guidelines, but nevertheless provide its own guidance documents. For example, in the UK, the regulator's top level of guidance is its Safety Assessment Principles (SAPs) (Office for Nuclear Regulation U.K., 2020), and these are supplemented by more specific details in documents which apply to particular technologies, called Technical Assurance Guidelines (TAGs) (Office for Nuclear Regulation, U.K., 2023). The TAGS reference international and national standards, which themselves are inter-related. Fig. 1 shows some of the standards for digital C&I systems used by the UK nuclear industry, with arrows representing how each standard is related to others. A summary of the different C&I standards relevant to nuclear plants is given by the World Nuclear Association, CORDEL (2020) (World Nuclear Association et al., 2020).

Although differences between standards and the national regulatory positions exist, a near universal principle is that systems with different levels of criticality, or 'importance to safety', require different levels of assurance. Plant safety functions are categorized according to how

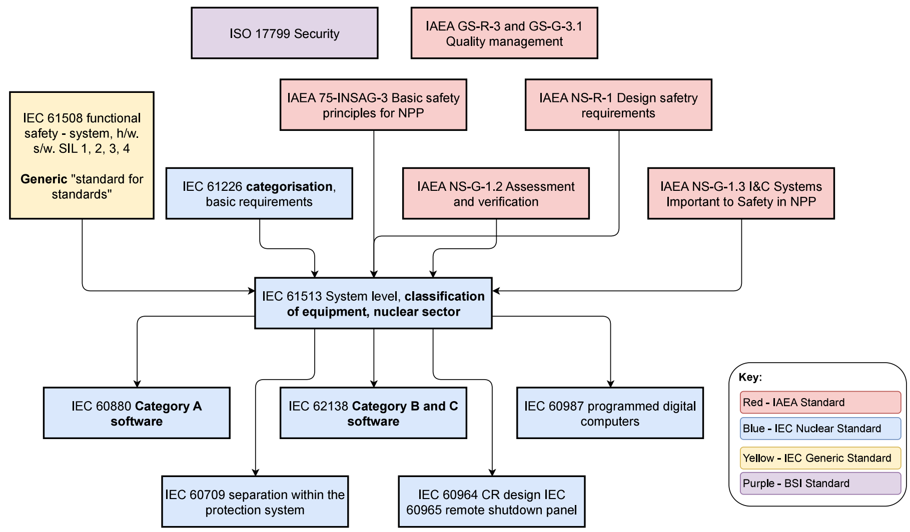

Fig. 1. Referenced standards in regulation of digital C&I for UK civil nuclear plants.

important they are to safety (World Nuclear Association et al., 2015) (e.g. Safety Categories A, B, C, as seen in Fig. 1). Systems are then further classified based on their role in providing these safety functions (e.g. 'safety critical', 'safety related', etc.). These categories are then used to specify the nature and degree of assurance activity required for those systems, typically involving the specification of reliability targets for each system. For example, in Fig. 1 the acronym 'SIL' in the standard IEC61508 refers to 'safety integrity level' which is a classification of the required reliability of systems: SIL 4 is highest integrity and correspondingly has the most demanding assurance requirements. In addition, a distinction is typically made between control of normal plant operation and control in accident scenarios. In nuclear plants, C&I systems managing everyday operation are considered lower criticality and, correspondingly, are only required to meet lower V&V requirements. Control & Management of the plant once it has entered accident scenarios is referred to as protection, which in nuclear applications typically involves plant shutdown and various engineered safeguard functions designed to manage this process. Plant shutdowns require special care, as these are not simple 'switch-off' procedures, for example, software-based management and control of heat removal systems necessary to avoid meltdown may be part of this function. Protection is considered high criticality. For example, although there are different parts of the plant protection system, the part where automated systems are entirely responsible for managing nuclear plant safety in rapid accident transients (i.e., accident scenarios where there is insufficient time for human intervention) is considered primary protection. Primary protection is classified SIL 4 in IEC61508 and as such is subject to the most intense safety assurance activities.

3.2.1. C&I wireless control

Some technologies, such as wireless communication, are regarded as more difficult to assure than others, creating an additional layer of complexity when trying to introduce these systems in operation. An existing safety standard for wireless communications in nuclear applications, IEC 62988 (BSI Standards Publication, 2022), deprecates the use of wireless communications in critical systems. However, this does not mean that an argument for the safety of such an application cannot be made, as local regulatory bodies (e.g. ONR in the UK) can decide not to mandate adherence to standards. In the case of a standard not being applied, a bespoke safety case is needed to justify such application so that it satisfies the regulator (e.g. ONR). Such a case might exploit particular features of an application, such as a simplicity of the communications requirements or the fixed nature of the communications environment. Similarly, it might deploy powerful

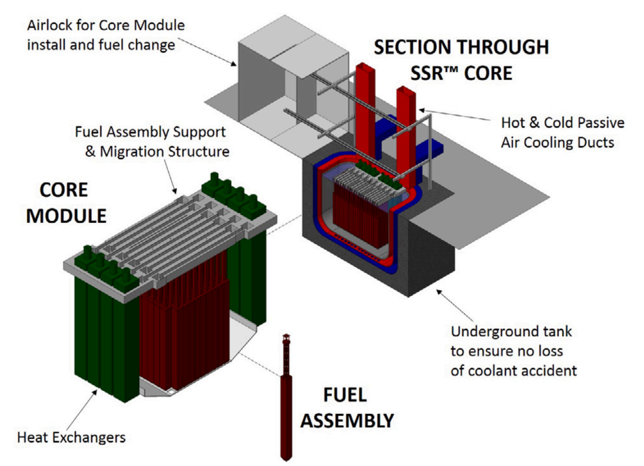

Fig. 2. Modules and core section of the Moltex Stable Salt Reactor (Moltex Energy LLP, 2023).

assurance methods such as formal proof of safety properties of the protocol, and the possibility of reliability-focused testing.

Given the previous discussion on criticality, the best space to deploy wireless technology is in lower criticality applications initially, but there is no reason in principle that higher criticality applications cannot be accepted by a regulator provided a compelling safety case can be made.

4. Stable Salt Reactor-Wasteburner (SSR-W)

The power reactor used for this feasibility study was the Generation IV Small Modular Reactor being designed by Moltex Energy, named the Stable Salt Reactor-Wasteburner (Scott, 2016). A general view of the current SSR-W design can be seen in Fig. 2. This feasibility study was done as part of the Intelligent Control for Nuclear (ICON) project (ICON, 2018).

This power plant is being designed to improve safety, sustainability, efficiency, and reduce overall costs. The Moltex SSR-W can be categorized in the family of Molten Salt Reactors (MSR), where the primary coolant or the fuel itself is a molten salt mixture at low pressure. However, the SSR-W makes use of fuel rods similar to conventional reactors do (see Fig. 2), separating the fuel from the coolant. SSR-W uses a mix of spent nuclear fuel from conventional reactors and sodium

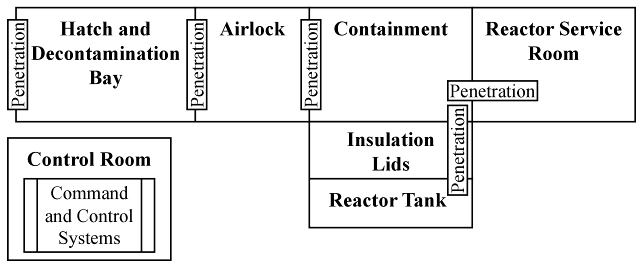

Fig. 3. High-level description of the Moltex Molten Salt Reactor (MSR) or Stable Salt Reactor, Wasteburning (SSR-W).

Table 1
SSR-W actuators.

ID	Value
Ax	Gantry crane drive actuator
Ay	Gantry car drive actuator
Az	Gantry handling car winch actuator
B1	Fuel handling car drive
B2	Fuel handling bayonet drive
C	PHEX Primary coolant pump drive
D	IHEX Secondary coolant pump drive
E	IHEX Tertiary coolant pump drive
F	Shutdown mechanism drive

Table 2
SSR-W sensors.

ID	Value
1a	Gantry crane torque signal (1 or 3)
1b	Gantry crane displacement signal (1 or 3)
2a	Fuel handling car torque
2b	Fuel handling car displacement
3a	PHEX Primary coolant pump inlet temperature signal (8)
3b	PHEX Primary coolant pump velocity signal (8)
4a	IHEX Secondary coolant pump temperature signal
4b	IHEX Secondary coolant pump velocity signal
5a	IHEX Tertiary coolant pump temperature signal
5b	IHEX Tertiary coolant pump velocity signal
6	In-core flux signal (fuel assembly placement — 1 per assembly)
7a	In-core flux signal (end of fuel channel placement – 2 per channel)
7b	In-core temperature signal (end of fuel channel placement — 2 per channel)
8	In-core flux signal (in-core well placement — multiple)
9	In-core power range flux signal (well placement)
10a	Ex-core power range flux signal (ground placement — multiple)
10b	Ex-core power range flux signal (outside — multiple)
11	Shutdown mechanism displacement signal (multiple)

chloride, which makes it economically and ecologically interesting to reuse nuclear waste.

Relevant features of the SSR-W regarding safety and control are its refuelling system, inherent safety features and modular design. Each fuel assembly is placed within a row within a rectangular grid of fuel assemblies, which allows changing and manipulating fuel roads whilst powered up; spent fuel and fresh fuel assemblies can be stored and interchanged inside the reactor itself, allowing to control the operation's reactivity via temperature coefficient and the refuelling process itself. The SSR-W has a negative fuel temperature coefficient of reactivity, meaning that higher temperatures reduce the amount of power and heat generated, making it self-controlling as long as heat can be extracted from the fuel tubes. Additional operational benefits include no high pressure required or generated and no additional hazardous substances such as iodine and caesium generated. The modular design of the SSR-W allows for the design seen in Fig. 3 to arrange up to 8 core modules fitted as a single reactor tank (i.e., modular reactor tank with everything related to fuel assembly supports, heat exchangers, flow ducts, etc.); the SSR-W can generate up to 1200 Million Watts of electric capacity (MWe) from 150 MWe modules. The modular design facilitates builds of different sizes and energy capacities, facilitating its redesign.

4.1. Refuelling system

As previously mentioned, the refuelling system is a crucial aspect of the SSR-W operation, as the fuel assemblies play a role in controlling the power output of the system. In addition, it is the only control system not dealing with a thermic reaction itself but with motion control (i.e., moving fuel assemblies in, out and around the reactor core). Fig. 4 shows a detailed schematic of the sensors and actuators in the different areas of the SSR-W. Tables 1 and 2 show the actuators and sensors numbered in Fig. 4. The Reactor Refuelling System is made of an overhead Gantry with x–y–z motion and a fuel handling car with bayonet for fuel assembly manipulation. The overhead Gantry has a Gantry crane for horizontal x-axis motion, a Gantry car for horizontal y-axis motion, a winch for vertical z-axis motion, and a car and bayonet for fuel assembly grasping and shuffling inside the reactor, as seen in Table 1. Each actuated axis has a torque and displacement sensor associated to it, as seen in Table 2. Motion for both the Gantry crane and Gantry car are designed to be driven by DC motors, whilst the winch and bayonet would be driven by stepper motors.

The Refuelling System deals with three crucial operations: to move fuel assemblies from a trolley in the airlock to a heating slot inside the reactor. To shuffle fuel assemblies inside the reactor (e.g., shuffle between spent rods and fresh rods to reach a desired operational temperature). To move fuel assemblies from a cooling slot inside the reactor, to a trolley in the airlock. These operations follow a control scheme that drives high-level commands from the control room to a master sequencer controller, which in turn drives the actuators in each of the axis following a sequential logical loop based on reaching certain positions on each axis. These operations deal with moving the fuel assemblies (i.e., around 100 kg) and the overall overhead structure (i.e., around 8000 kg), but there are no time constraints during operation hence, they do not require considering fast acting dynamics for any control purposes. The available positions inside the reactor for the fuel assemblies are fixed and known in advance. As no time constraints are considered for any of the gantry's operations, we can restrict fuel assembly manipulation to happen at a nominal slow pace. Furthermore, it implies that any delays present in the system can be planned and designed for, in order to accommodate the system's dynamics.

The incorrect insertion of a fuel assembly into the fuel supply trolley will not lead to radiation leakage beyond the airlock/containment. This is because, even if the fuel assembly is damaged, the fuel is held within salt which is solid at the temperatures found in these locations. The safety criteria of the operations and functions for the Refuelling System are below the highly stringent characteristics for Safety Category A or Category B (i.e., functions that play a principal or complementary role for power plant safety), hence are classified as Category C. This system is ideal to design a wireless system around, due to its functions being of Safety Category C.

5. Wireless control system feasibility analysis

5.1. Environmental constraints for wireless transmission

Based on the Refuelling System described in Section 4.1, a feasibility study for the design and application of a wireless-based control system was developed. Fig. 5 describes the specific communication channels proposed for in-containment wireless communication of the Refuelling System described in Section 4 and Fig. 4. In Fig. 5, two wired communication links (A and B) are proposed between the high-level control logic in the control room and the in-containment devices, mediated by a transceiver (E) placed between the Airlock and the Containment areas. The wireless communication link (B) is proposed to connect the transceiver (E) and the low-level logic devices controlling the Gantry

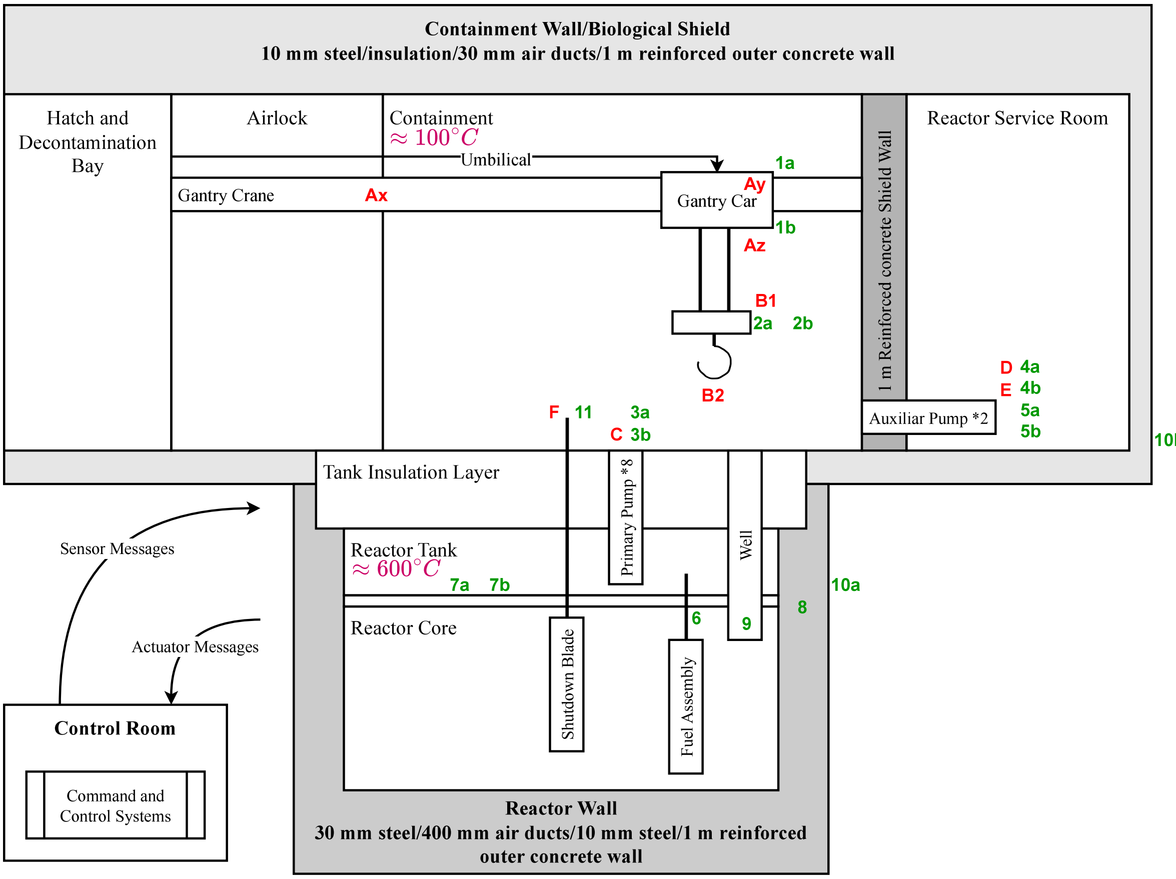

Fig. 4. Schematic of SSR-W layout with sensors and actuator locations.

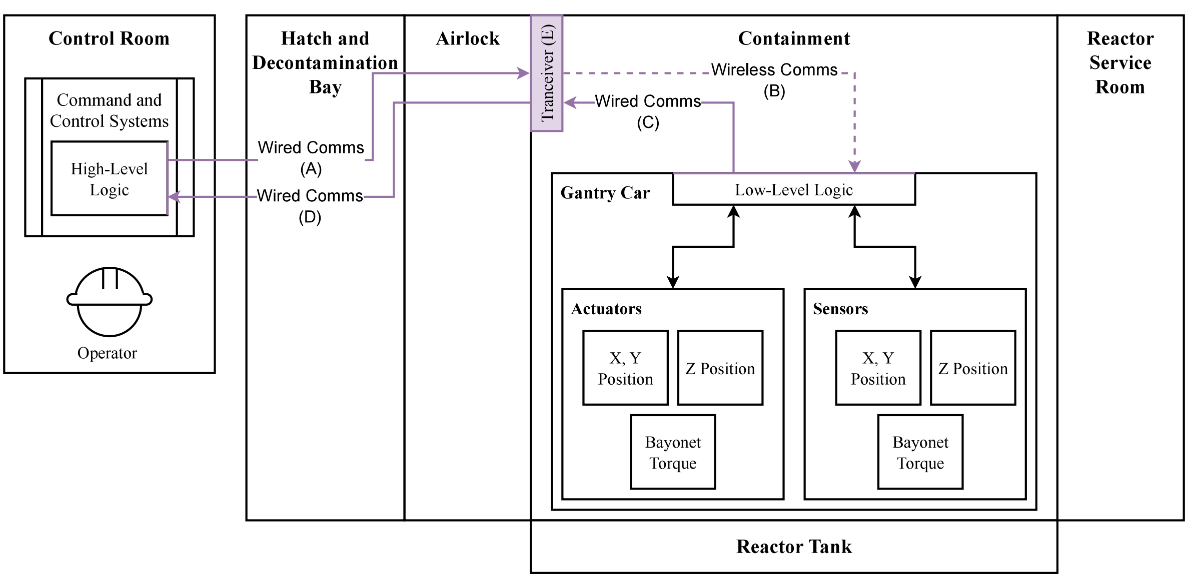

Fig. 5. Communication links and control logic for the SSR-W Fuel Management System (FMS) with wireless based C&I for Gantry car control.

System. The existing wired communication link (C) between the low-level logic devices and the transceiver (E) is left as the main relay link to feed sensor and process data to the Control Room. The Low-level logic would also have a transceiver device, to transmit and receive wireless signals to the transceiver (E), but it is not highlighted in the figure. This configuration was considered for the sake of simplicity for the feasibility study, as there is no strong contradiction in having C and B links being bidirectional or functioning in parallel as redundancy for system safety and robustness.

Recent advances in Wireless Sensor and Actuator Network technology (WSN) (Park et al., 2018) have transformed novel and robust C&I applications. WSN are built from nodes that either generate information from a process or sensor input, or consume information to be used in any internal or external process. Control applications with redundant information sources can be created on top of such distributed wireless sensors and actuators network. Civil nuclear applications such as power generation is a field that can benefit from such technologies, particularly due to the existence of hard to reach areas that make deployment, maintenance and decommissioning of assets a difficult process. However, technical requirements and environmental factors need to be considered when designing wireless sensing and actuation nodes, as it informs the wireless technology to use, node placement and power source.

The most common technology used for wireless communication involves generating electromagnetic waves as they propagate across the open space. As such, the means of transportation for these waves and any structure it interacts with can affect the overall signal quality. Environmental factors relevant to wireless channel integrity include temperature and humidity (Luomala & Hakala, 2015), the electromagnetic environment (Changlin, Zhan, Xuebing, Hongtao, & Weidong, 2008) and the physical properties of the physical layout (e.g. location, material, and geometry). In addition, ionizing particles such as high-energy gamma and neutrons have proved to affect electromagnetic waves, including time delay, Doppler effect, polarization rotation and attenuation (Millman, 1958).

Environmental factors relevant to nuclear power reactors are temperature and ionizing radiation, which would also affect electronic systems implementing any wireless technology (e.g., clock drift, overheating). However, temperatures in the containment and airlock sections of the SSR-W are expected to be around 100 °C with low radiation due to the cooling/insulating layer (Scott, 2016). Further compatibility analyses are needed before installing the wireless system, as to understand if further protection is needed to meet operational requirements. A common strategy to protect devices is the use of shields or absorbers around devices, with materials such as lead and concrete for gamma radiation and aluminium for beta and alpha radiation.

After understanding that wireless systems could both function and transmit data in containment, environmental factors affecting performance are analysed. The containment physical layout is limited by a set of walls and the movable metallic structure of the gantry system. The walls would generate a Faraday cage. This introduces an advantage and a disadvantage: The Faraday cage traps all signals inside the containment, i.e. introducing a form of cyber-security. At the same time, signal collisions are increased, degrading the wireless signal itself. In addition, the gantry would move transceivers during operation, affecting signal transmission by inducing subtle phenomena such as shadowing (Lu, May, & Haines, 2015). Such effects can be alleviated at the communication protocol level.

5.2. Protocol selection and performance

Selecting a wireless technology is tightly related to the communication protocol or standard defining such technology. Wireless communication dictates the potential performance and use of the network, as it determines allowed bandwidth, latency, point-to-point distance and power consumption. There are various standards for wireless communication that can be used in our application. Regarding power consumption, as these wireless nodes would be placed in a harsh area that is difficult to access, self-powered nodes with reduced energy consumption need to be considered. Considering an expected core diameter below $3\ \mathrm{m}$, distances between different transceivers would be inside the $100\ \mathrm{m}$ range. Latency would be an important aspect in this control application, as low and deterministic latencies help to ensure a desired control performance. Considering the lack of timing constraints for this application, we can expect a latency around $100\ \mathrm{ms}$ for sensor data and control commands. Large bandwidth is not required for this application, considering that due to the number of sensors and actuators, the expected transmission payload would not grow beyond <1 Mbps. This is calculated by considering two sensors per motion axes, each of float size (4 bytes), and command controls with two floats at max, adding to 6 bytes per axis, 30 bytes in total or 300 bytes per second, well inside the 250 kb per second that many modern protocols can manage.

Popular wireless protocols working in the industrial, scientific, medical (ISM) frequency band of 2.4 GHz, like IEEE 802.11 (Wi-Fi) and IEEE 802.15.1 (Bluetooth) can offer a sufficiently high data rate. However, they do not support large number of network nodes, especially with very low-power consumption (Wang & Jiang, 2016). In contrast, IEEE 802.15.4 offers the advantages of economical battery usage, flexibility in the number of nodes and mesh networking, thus making it more suitable for process automation applications (Baker, 2005; Bertocco et al., 2008; Delsing, Eliasson, & Leijon, 2010; Kadri, 2012). IEEE 802.15.4 has been upgraded to IEEE 802.15.4e to provide improved operational performance for process automation applications. The upgrades include additional Media Access Control (MAC) functionalities, such as Time Slotted Channel Hopping (TSCH) and Deterministic and Synchronous Multi-channel Extension (DSME). The nodes within the TSCH network are fully synchronized, and each node in the network has a specific timeslot that is used to exchange information with the adjacent nodes (Al-Nidawi & Kemp, 2015). The time slotting helps save energy, as it reduces the nodes' radio duty or time the radio must be on listening for incoming messages. In addition, Time Synchronization and Frequency Hopping reduce interference, helping to produce a deterministic low latency network necessary for control. A typical system timing between messages in a TSCH network is of $10\ \mathrm{ms}$, which is well inside the expected delay of $100\ \mathrm{ms}$.

An initial estimation of the expected performance of a TSCH-based wireless node for the motion control needed in the Refuelling System further confirms the validity of this technology. Studies suggest that TSCH is a flexible solution, as power consumption and latency can be tuned to achieve a wide range of applications (Scanzio et al., 2020). TSCH does not require changing the physical layer, allowing it to operate on any IEEE802.15.4-compliant hardware (Thubert et al., 2013). When considering the motion in the vertical z-axis and inside the reactor (i.e. winch and bayonet), both use stepper motors and drive lighter loads ($<1000\ \mathrm{kg}$). Stepper motors can be driven by stable open loop controllers with a defined sequence, only requiring commands from High-Level Logic to change reference position but, such positions are defined by the state of the refuelling process and do not change constantly. In contrast, motion in x and y-axes (i.e. Gantry crane and Gantry car) uses DC motors with a ball screw drive to move most of the overhead structure ($\approx 8000\ \mathrm{kg}$) and do require a closed-loop controller for stable position control. DC motors allow direct speed control and require a sensor measurement from a position sensor (e.g., optical encoder or resistive sensor) to control the motor's speed and reach the desired position. A closed-loop controller can be designed by considering a brushless DC motor of $48\ \mathrm{VDC}$, $\approx 8\ \mathrm{A}$, $110\ \mathrm{N\ m}$, $110\ \mathrm{rpm}$ and a wireless network built on IEEE 802.15.4 TSCH (Rzepecki, Iwanecki, & Ryba, 2018) with a delay between messages of $10\ \mathrm{ms}$. Considering a sampling period of $10\ \mathrm{ms}$, control analysis methods confirm that delays in both sensor-feedback and control action of up to 10 times the sampling time are easily acceptable. It is worth considering that the low-level logic in Fig. 5 could include a wired connection to the position sensors, eliminating the sensor-feedback delay in the position control if needed. Considering the potential of environmental impact to control performance, testing would be needed to assure adequate performance in the actual application.

5.3. Powering options

Regarding powering of the wireless nodes, different options were considered. Batteries offer some advantages, but their short life compared to a power plant's expected life (i.e., years to decades) is challenging, specially in an application with areas difficult to reach. High-temperature and active radiation environments are not suitable for normal batteries, as it can reduce efficiency and cause malfunctioning.

In addition, batteries are difficult to decommission, as they would add extra steps to the expected strategy of melting most of the SSR-W components. Therefore, battery-independent, self-sustaining options were explored.

The process of obtaining energy from an external renewable source and storing (i.e., Energy harvesting) is a relevant topic for WSN and for our application (Singh, Kaur, & Singh, 2021). The waste heat in the containment area can be harvested using a thermoelectric material to generate electricity. Converting heat into useful electricity has been used in space-bound objects and other remote structures through using radioisotope thermoelectric generators (RTGs) (Jiang, 2013). The RTG uses radioactive materials to generate heat, which is then converted into electricity by an array of thermocouples. The expected temperature of 100 °C in containment might be high enough that RTGs may not be necessary.

As a point of reference, previous studies have shown the use of a thermoelectric energy harvester capable of generating enough power to operate a wireless sensor (Chen et al., 2016). Such thermoelectric generator-based harvesters were shown to work at temperatures from ≈290 °C up to ≈320 °C. Alternative approaches could harvest energy from highly energetic background radiation, even if such radiation is largely suppressed in the containment area. High-efficiency photovoltaic cells for X-ray harvesting, based on methylammonium lead iodide, CH3NH3PbI3, Náfrádi et al. (2020) and Náfrádi, Náfrádi, Forró, and Horváth (2015), have been shown to both protect from radiation and to produce electricity at 0.3 mW/kg of power density in environments with 50 Sv/h dose rates. Such RTGs could power a wireless node for our control application, if considering a nominal power consumption whilst transmitting of 10 mA (Rzepecki et al., 2018) and a consumption whilst in idle state <1 mA. Such consumption would be well inside the theorized maximum power output of 2.25 W or 680 mA for 3.3 V Integrated Circuits reported in previous studies (Chen et al., 2016). In contrast, any associated sensors and actuators for the Refuelling System should be powered by a mains wired cable, as they often consume more than 1 A (e.g., optical encoders 5 VDC, ≈80 mA, stepper motors 120 VAC, ≈5 A, and DC motors 48 VDC, ≈8 A).

Considering the analysed environmental requirements for deployment, the performance requirements regarding closed-loop control, the aspects of feasible wireless communication protocols and its self-powering solutions, we believe there is strong evidence to suggest that a wireless-based control node for this application is technically feasible.

6. Safety assessment

By having a feasible technical candidate for the wireless control of the refuelling system of the SSR (see Section 5), further analyses can be done around the implementation of such system. Any C&I solution deployed as part of a nuclear reactor system must be demonstrated to be acceptably safe for its intended use. This requires safety analysis to be carried out within the context of the intended usage and application environment. Here, we present the initial results from a safety analysis using a hazard-based technique, and considering a potential route to constructing a safety argument. A considerably broader, in-depth analyses will need to be completed as part of the development and deployment of such a system.

6.1. Safety considerations

An initial, high-level safety analysis was carried out to investigate the safety implications of the proposed solution. The safety analysis approach was to conduct a HAZard and OPerability (HAZOP) study (BSI Standards Publication, 2016). Although initially developed to analyse chemical processes within a production plant (Kletz, 1997), HAZOP has found broad application across a range of domains, including software-based systems. The HAZOP technique was chosen because it provides a structured and systematic technique for system examination and hazard identification.

The HAZOP methodology is a team activity, with subject-matter experts employing brainstorming to explore potential deviations from a system's design intent. The focus is on deviations in the expected inputs/outputs that flow between sub-systems within the system being analysed, and how these deviations may affect the outcome of the system (i.e. a cause/consequence analysis). The subject-matter experts predict deviations based on their knowledge of the system under investigation, their experiences, and general subject expertise.

The identification of deviations from the design intent is achieved by a questioning process using predetermined guide words. The aim is to encourage lateral and imaginative thinking to identify all plausible deviations from the system's design intents. The guide words used at this initial analysis are typical of those used in HAZOPs. The key to a successful HAZOP is to interpret the guide words in the broadest possible sense, within the context of the system of interest.

The guide words used, with an example interpretation, are:

No/Not : Message not transmitted
More/Greater : Message transmitted more than once
Less/Fewer : Only part of the message transmitted
Late/After : Delay in transmitted message reaching intended destination
Early/Before : Transmitted messages arrive out of sequence
As well as : More than one message transmitted
Reverse : Message transmitted in the wrong direction
Other : Any other deviation that springs to mind

The focus was given to end-to-end communications between the Control Room and the actuators and sensors placed in the containment. As introduced in the use case description (see Section 4.1) the gantry-based crane operation during refuelling, fuel shuffling, and defuelling of the Molten Salt Reactor was investigated.

The system of interest can be seen in Fig. 5, describing the communications channels between containment and control room. The interfaces and/or functions examined within the system were:

(A) Wired Communication link between High-Level Logic interface and Transceiver.
(B) Wireless Communication link between Transceiver and Low-level Logic interface.
(C) Wireless Communication link between High-Level Logic interface and Transceiver.
(D) Wired Communication link between Transceiver and High-Level Logic interface.
(E) Transceiver.

Each interface and/or function was considered during all the operational stages of the refuelling system, such as:

- Crane moving fuel assembly from trolley in airlock to heating slot in reactor.
- Crane shuffles fuel assembly in reactor.
- Crane moves fuel assembly from cooling slot in reactor to trolley in airlock.

As a result of the HAZOP, the following safety implications were identified:

- Damaged fuel assembly (ex-core and in-core).
- Fuel assembly fouls (ex-core and in-core).
- Unburned fuel placed in storage/recycled (ex-core).

Within the analysis undertaken, all the safety implications resulted in operational Health and Safety issues, rather than postulated incidents.

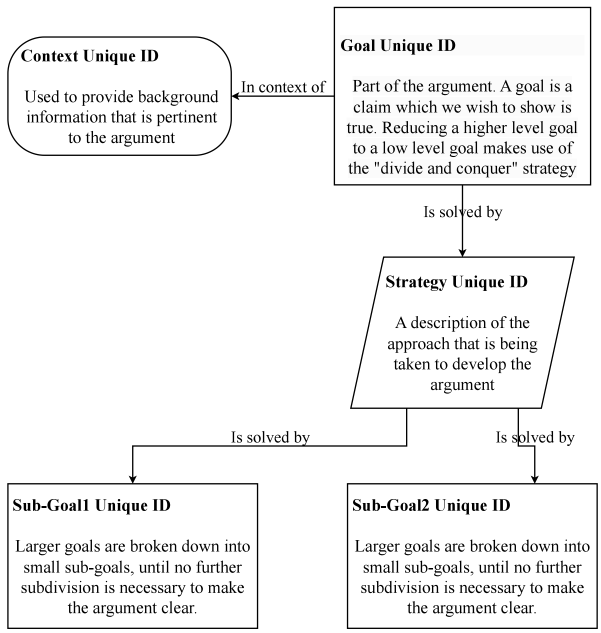

Fig. 6. Goal Structuring Notation node types used.

This initial HAZOP will need to be extended to investigate component failures, with failure modes qualified and safety requirements identified. The analysis from the HAZOP will also provide input into other safety analysis activities, and the safety argument.

6.2. Safety argument

Any safety related C&I system must be demonstrated as acceptably safe for its intended use. One way of demonstrating this is through a safety argument (Kelly & Weaver, 2004).

A high-level safety argument was created to support the claim that *"Wireless system C&I for use within the SSR-W Fuel Management System is acceptably safe and As Low As Reasonably Practicable (ALARP)"*. The argument was developed using Goal Structuring Notation (GSN) (The Assurance Case Working Group (ACWG), 2021).

Within GSN, Goals are recursively reduced into sub-goals, to the point at which the lowest level child goals can be demonstrated as true, through tangible evidence (e.g., testing, analysis, documentation, a separate safety argument) (Matsuno & Yamamoto, 2013). Strategies may be included in the argument, between a parent and its child's goals, to help guide the reader. Context is used to state anything that bounds the argument (e.g., definitions, description of system with boundaries of safety argument, limitations in applicability of safety argument, applicable standards).

Only a subset of the available GSN node types have been used within this outline safety argument. The nodes and their relations are described in Fig. 6.

In the context of the conducted feasibility study, this safety argument offered a first look at how the use of wireless-based C&I within the Fuel Management System (FMS) of the Moltex SSR-W may be shown to be acceptably safe. It was used as a vehicle to investigate some of the typical topics that would be considered within any final safety argument. It also provided the means whereby the various research threads within the feasibility study could be discussed, including issues explored, the mechanism for conclusions to be drawn, and future work to be identified.

The initial safety argument in GSN notation can be seen in Fig. 7. The top goal (G1) is used to state what will be demonstrated, the context for the argument (i.e. Cxt1 through Cxt9), and the strategy (St1)

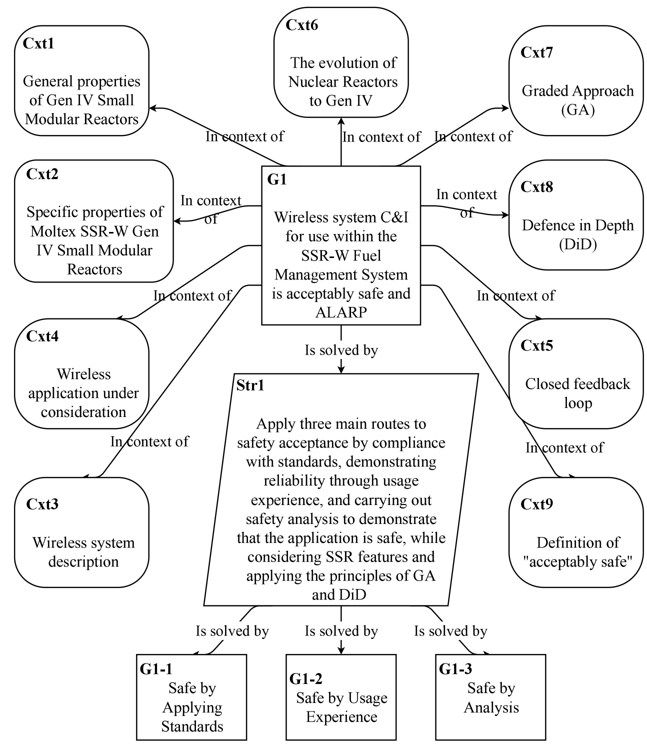

Fig. 7. Safety argument using Goal Structuring Notation of wireless based C&I within the FMS of the SSR-W.

being used to demonstrate that the high-level goal is true. This strategy resulted in the top-level goal being decomposed into three sub goals.

G1-1 is a sub-goal related to the use of standards. One way to argue that wireless-based C&I is safe is by showing compliance to relevant Nuclear Power Plants (NPP) international standards, recognized good practice (RGP), and guidance. Existing standards for the use of wireless-based C&I are written in the context of Generation II and Generation III NPP. These standards take a conservative approach to the use of innovative technology, and as such place restrictions on the use of wireless-based C&I in systems that are important to safety. There are currently no standards that relate specifically to Generation IV Small Modular Reactors (SMR), acknowledging the difference in risk profile that may exist between Generation II/III and Generation IV reactors. It was concluded that the regulatory framework should be revisited, and if appropriate, updated to meet the needs of Generation IV reactors. The UK Nuclear Regulator has indicated that they may be willing to consider safety arguments for wireless-based C&I on a case-by-case basis. Moreover, updated regulation would help to support this approach.

G1-2 is a sub-goal related to the use of existing data to demonstrate future safety. To develop this part of the argument, the existing data will need to be directly comparable to the proposed future usage, with any differences identified, managed, and mitigated. There is considerable use of wireless systems in NPP. However, wireless systems are not used by critical systems or in the harsh environmental conditions considered by this outline safety claim. There are several safety claims made by existing use and research, but these claims would need further exploration for quantification, in terms of:

- Can wireless-based C&I deliver a cost-effective means to achieve measurement redundancy and/or diversity in closed and open loop, through the use of more sensing points, without compromising plant safety?
- Can wireless-based C&I prevent unexpected total-failure, and support predictive maintenance, through continuous condition monitoring, reducing downtime and person power, while improving

plant economy, safety, availability, and in some cases, reducing staff exposure to radiation (e.g. inside containment)?
- Can wireless-based C&I provide post-accident monitoring, where it may be difficult to obtain credible readings from wired systems?
- Can wireless-based C&I be designed with better and robust diversity techniques compared with those of wired systems? Therefore, offering improved reliability and more operating flexibility.

The three main concerns regarding the use of wireless in a NPP are:

- Electromagnetic and radio frequency interference.
- Reliability (including signal coverage, software reliability, and reliability/longevity of power supply).
- Cybersecurity.

The experience of using wireless technologies and components, including those developed for harsh environments in other industries like the Space industry, may possibly be utilized to support wireless applications in NPP. However, existing technology is likely to need adaption or customization for future NPP usage.

An alternative approach would be to use evidence based on the implementation of both a wired and a wireless-based version of the same C&I system in parallel. Initially, primary dependence will be on the wired system. The operational experience gained with the wireless system being used as a 'shadowing' system may be used to gain confidence and contribute to a safety case for wireless C&I systems. Any parallel implementation must ensure non-interference between the systems. It may be possible to justify the extra risk that a parallel implementation of systems brings by the increase in quality and quantity of data once the wireless system has been reliably established, and the improvements in management that it may bring.

G1-3 is a sub-goal related to the use of a typical approach to safety arguments, confirming that the hazards have been identified, and the risk associated with these hazards is shown to be managed to an acceptable level.

An initial HAZOP has been carried out to analyse the hazards and safety implications inherent in the use of a wireless based C&I system for fuel movements between the airlock and the containment. As seen in Section 6.1, the safety implications identified by this HAZOP carry a lower safety risk compared to the risks experienced within Generation II/III reactors. Furthermore, further HAZOPs are required once a design is finalized, to understand further risks and its hierarchy across boundaries.

7. Conclusions

In this work, we proposed a configuration using a wired solution from command room to containment unit, for the use of wireless nodes for closed-loop control inside the containment unit of a Gen IV Stable Salt Reactor.

We detail the methodology followed, and the results obtained, during the development of a wireless control system for a system operating inside a civil nuclear power plant. Our feasibility study indicates that there is technical basis to consider the creation of a wireless control system for the low-safety functions (Safety Category C) of the Gantry Refuelling System of an SSR. Our initial safety assessment showed that, in principle, there is no reason why a safety case cannot be made to implement wireless control in our specific use case scenario.

There remain additional obstacles that will need to be overcome before wireless technologies can be used in the novel way proposed by this paper. Some of these are technical, such as the assurance that components can withstand the harsh environmental conditions, or the harnessing of a power supply that is safe and reliable in the harsh environmental conditions. At the same time, Control over Network Methods allow in principle for an integrated co-design of robust control and communication structures, e.g. Longo et al. (2013). Other obstacles are regulatory. The current standards deprecate the use of wireless technologies in nuclear power plants for critical C&I. This feasibility study has shown that technical innovators and regulators should work together to further understand the safety-related issues associated with wireless-based C&I, subsequent closed-loop control, and the ways in which these issues can be managed and mitigated, with a view to taking full advantage of the possibilities (or innovations) that wireless-based C&I offers.

Future work will focus on initial implementations of wireless control schemes for systems with functions such that its dynamic and safety characteristics fall in Safety Category C (i.e. ancillary functions where failure is not critical to operation). A more complete safety analyses will follow, which will consider creating safety assurance and the V&V implications of a wireless control scheme for a Safety Category C function.

CRediT authorship contribution statement

Erwin Jose Lopez Pulgarin: Methodology, Software, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Guido Herrmann:** Conceptualization, Writing – original draft, Writing – review & editing, Supervision, Funding acquisition. **Christine Hollinshead:** Conceptualization, Resources, Writing – original draft, Writing – review & editing, Visualization. **John May:** Conceptualization, Resources, Writing – original draft, Writing – review & editing, Supervision, Funding acquisition. **Kibrom Negash Gebremicael:** Methodology, Software, Formal analysis, Investigation, Writing – original draft. **Diane Daw:** Conceptualization, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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