BJRS
BRAZILIAN JOURNAL of RADIATION SCIENCES
doi.org/10.15392/2319-0612.2024.2714
2024, 12(4B) | 01-26 | e2714
Submitted: 2024-08-30
Accepted: 2025-06-11

Use of Augmented Reality in the Design of Land Facilities Supporting Nuclear-Powered Submarines

Canuto[a], C. L.; Reis[a], R. T.; Oliveira[a], P. C.; Baroni[*b], D. B.; Marcos[c], T. R.; Borsoi[d], S. S.; Diniz[a], G. N.

[a]Fundação para Desenvolvimento Tecnológico da Engenharia – FDTE
[b]Amazul
[c]BK Consultoria e Serviços Ltda
[d]Diretoria de Desenvolvimento Nuclear da Marinha - DDNM

*Correspondence: dbbaroni@gmail.com

Abstract: This paper addresses the potential applications of Augmented Reality (AR) in the design and operation of nuclear facilities, focusing on terrestrial support facilities for nuclear-powered submarines. The inherent complexity in developing these submarines demands continuous innovations, including the design of their land-based support facilities. AR emerges as a promising perspective, allowing high-tech approaches to specific challenges in the design and operation of these facilities. The study presents an initial application of AR aimed at evaluating the integration and functionality of the proposed setup (computer, AR smart glasses, application, file conversion and transfer processes, etc.). Once the operability of this setup is validated, a list of applications (in development) is proposed to highlight the potential contributions of AR in the development of land-based support for nuclear-powered submarines. To validate the exploratory approach methodology, the proposed initial AR application includes the demonstration and display of three-dimensional models and their integration into the physical environment using commercial AR smart glasses and application. The results of this initial application suggest promising prospects for future applications. The list of AR applications under development ranges from the design phase to operation, including nuclear licensing, construction phase, operation, safeguards, physical protection, and quality assurance. It is concluded that the use of AR has potential to contribute to the development of land-based support facilities for nuclear-powered submarines, although further studies are needed to confirm its practical application and effectiveness.

Keywords: nuclear-powered submarines, augmented reality, nuclear licensing.

doi.org/10.15392/2319-0612.2024.2714
2024, 12(4B) | 01-26 | e2714
Submitted: 2024-08-30
Accepted: 2025-06-11

Uso da Realidade Aumentada no Projeto de Instalações Terrestres que Suportam Submarinos com Propulsão Nuclear

Resumo: Este artigo aborda as possibilidades de aplicação da Realidade Aumentada (RA) na concepção e operação de instalações nucleares, com foco em instalações terrestres de apoio a submarinos com propulsão nuclear. A complexidade inerente ao desenvolvimento desses submarinos demanda inovações contínuas, incluindo a concepção de suas instalações terrestres de suporte. A RA surge como uma perspectiva promissora, permitindo abordagens de alta tecnologia para desafios específicos no projeto e operação dessas instalações. O estudo apresenta uma aplicação inicial de RA com o propósito de avaliar a integração e funcionalidade do arranjo proposto (computador, óculos de AR, aplicativo, processos de conversão e transferência de arquivos etc). Validada a operabilidade deste arranjo, propõe-se uma lista de aplicações (em desenvolvimento), visando elencar as possíveis contribuições da RA no âmbito do desenvolvimento de suporte em terra a submarinos com propulsão nuclear. Para validar a metodologia de abordagem exploratória, a aplicação inicial de AR proposta inclui a demonstração e exibição de modelos tridimensionais e sua integração ao ambiente físico utilizando um óculos e aplicativo comercial para RA. Os resultados desta aplicação inicial permitem vislumbrar o emprego em aplicações futuras. A lista de aplicações de AR em desenvolvimento compreende desde a fase de projeto até a operação, incluindo licenciamento nuclear, fase de construção, operação, salvaguardas, proteção física e garantia de qualidade. Conclui-se que a utilização da RA tem potencial para contribuir com o desenvolvimento de instalações terrestres de apoio a submarinos com propulsão nuclear, embora sejam necessários estudos adicionais para confirmar sua aplicação prática e efetividade.

Palavras-chave: submarinos com propulsão nuclear, realidade aumentada, licenciamento nuclear.

1. INTRODUCTION

Augmented Reality (AR) has demonstrated benefits across various domains, such as training, simulation, remote assistance, inspection and repairs, and knowledge capture. Through the use of portable electronic devices such as tablets, smartphones, or AR smart glasses, this technology incorporates virtual elements into the real world, creating a visual experience that transforms perception and interaction with the environment and structures, thanks to the fusion of these virtual and real elements. Reports indicate that AR innovations are emerging in sectors like consumer goods, retail, architecture and construction, professional services, and education. In these cases, AR tools are creating new sales and marketing experiences, improving operational efficiency, enhancing engineering quality, and enabling the creation of new products and services. Companies across different sectors are leveraging AR to boost productivity, improve accuracy, and satisfy their employees. Technology giants, as well as major consulting firms, are leading this transformation, while innovative startups are developing AR-specific platforms for novel applications and for sectors with high complexity involved in their needs. [1]

In this context of complex applications, the nuclear field presents considerable challenges, and high expectations for AR applications. Beyond the nuclear aspect, the integration of naval facilities and operations makes the design of land facilities supporting nuclear-powered submarines a field of countless of possibilities for AR use at the highest level of complexity. These facilities demands continuous innovations that extend beyond the confines of their conception, construction, and operation. In this regard, the intersection of military (defense), nuclear, and naval aspects establishes the design of land support facilities for nuclear-powered submarines as a technological paradigm as intricate and sizable as the development of the submarines themselves [2-5]. Beyond both conventional [6-8] and nuclear applications [9-11], Augmented Reality (AR) emerges as a promising perspective, enabling high-tech approaches and solutions for specific challenges both in the design and the operation of land support facilities for nuclear-powered submarines.

This paper presents an initial application of AR and proposes a list of possibilities, still under development, aiming to explore and integrate AR as a strategic tool in the development of land support facilities for nuclear-powered submarines. The goal is to contribute to nuclear licensing, safeguards, design, construction, and operation.

With a specific focus on the Specialized Maintenance Complex (CME, in portuguese), designed to provide land support structures and systems for the first brazilian nuclear-powered Submarine (Submarino Nuclear Convencionalmente Armado – SNCA) - both under development by the Brazilian Navy, it is anticipated that the use of AR can introduce new features and possibilities, making the interaction between the technical teams and other stakeholders in the project more efficient and effective.

1.1. Immersive technologies: AR x VR

The use of Augmented Reality (AR) immediately prompts a reflection on its use and comparison with Virtual Reality (VR) in terms of their applicability, advantages, and disadvantages. Both are immersive technologies that transform the way users interact with digital models. The choice of the most appropriate technology depends on the specific objective of the application, and in many cases, AR and VR can be used in hybrid methods to complement each other. The distinct characteristics and applications of AR and VR are shown in Table 1.

Table 1: Brief comparison and recommended applications: AR x RV

Criterion	Augmented Reality (AR)	Virtual Reality (VR)
Level of Immersion	Partial, overlaying digital elements onto the real environment.	Total, completely replacing the real environment.
Interaction	Allows interaction with both physical and virtual objects simultaneously.	Fully digital, without interaction with the physical environment.
Training	Ideal for interactive training in real environments, such as inspections and maintenance.	Best for complex simulations and training for critical situations.
Design & Engineering	Facilitates the visualization of 3D models in the real environment, aiding in project compatibility verification.	Excellent for design testing and concept validation before construction.
Operational Efficiency	Enables the overlay of useful information for real-time assistance.	Useful for testing operations in a virtual environment before real-world implementation.

On one hand, VR allows the creation of a completely digital and immersive environment, isolating the user from the real world. On the other hand, AR stands out in integrating the real world with virtual elements, providing direct interaction with physical installations. This capability makes AR particularly well-suited for research objectives. In the nuclear context, AR can assist in maintenance, inspections, and real-time operations. During the design and construction phase, AR enables better identification of problems and failures, as well as real-time implementation of corrections. Additionally, in the nuclear licensing process, AR can be used to virtually demonstrate a facility's compliance with regulations, facilitating audits and inspections.

However, it is important to note that, in general, AR glasses also allow for VR applications, such as the glasses used in this study. Therefore, the term "Mixed Reality" has become common. As an example of this integration between AR and VR technologies, it is possible (with the software used in this study) to start visualizing in reduced scale 3D model in AR, and as the model is explored, the user can be virtually inserted into the model and made to navigate in real scale using VR.

2. MATERIALS AND METHODS

The success and functionality of the application relies on all elements involved in the established arrangement, starting with a well-crafted 3D model and the appropriate choice and configuration of AR devices technology and performance, and the application and its correct configuration for viewing with the devices. Thus, to validate the methodology, integration, and functionality of the arrangement used, initially the 3D models were developed through the Building Information Modeling (BIM) method, and the integration of the 3D model into the physical environment was carried out using commercially available Augmented Reality (AR) smart glasses with an application for visualization (Figure 1).

Figure 1: AR smart glasses

Source: authors

To that end, for exporting of the models (from the original computer where they were developed to the AR smart glasses used), it was first necessary to ensure that they were in the appropriate format, compatible with the virtual and augmented reality devices to be used. This process involved converting the original files to a format accepted by the AR smart glasses, preserving as much detail and precision of the original architectural elements as possible. During this stage, the focus was to ensure that textures, proportions and the positioning of elements were maintained according to the original design to provide an immersive and realistic experience for the end user.

Applications and other proposals for using Augmented Reality (AR) resources in the design of land support facilities for nuclear-powered submarines are listed below and are currently under development/analysis:

- Demonstration and Exhibition
- Design Phase
- Nuclear Licensing
- Construction Phase
- Operation
- Safeguards
- Security
- Quality Assurance

The following section will conceptually describe all the mentioned AR applications, including the description of two cases for the Demonstration and Exhibition application.

2.1. Demonstration and Exhibition

This function of Augmented Reality is intended to assist in the visualization of project integration into the site before construction, as well as to explore variations in layout, spatial configuration, and design components. Additionally, it contributes for technical solutions in project meetings and supporting decision-making. For this purpose, the process involved the use of two distinct BIM models, each with specific characteristics and different purposes in AR: visualization of the original project and the visualization of virtual elements on the physical environment.

The first model consisted of a simplified digital model of a land-based support facility for nuclear-powered submarines. The project of the Specialized Maintenance Complex (CME), being developed by the Brazilian Navy in Itaguaí/RJ, was used as a reference. In addition to the detailing of the structures, it was necessary to consider the scale and representation of the different areas of the development so that they could be adequately explored and analyzed in conjunction with a physical environment. This application was not solely for visualization purposes but also for the interaction and analysis of specific components of the project, enabling future applications to interact with the 3D model in a more dynamic and intuitive manner.

The second model consisted of a set of pipes, ducts and fire-fighting system, designed to integrate into the reference room, where the main challenge was to ensure that the dimensions and incorporation with the virtual environment faithfully replicated the conditions of the physical space. Since the model would be used for display and presentations, demonstrating the potential use of AR technology, it was essential that the integration of the virtual items with the physical environment was precise. This requirement not only facilitates the implementation of future applications for project visualization but also allows for early identification of potential adjustments, contributing to the efficiency of project development and its subsequent construction.

2.2. Design Phase

The inherent complexity of using nuclear technology and the potential risks and consequences associated with operational incidents need the implementation of technologically advanced tools in the development of nuclear facilities designs. AR can offer capabilities that align with the level of complexity and the demands of the nuclear industry, enabling the optimization of complex infrastructure designs and contributing to the safety of the workers, the general population, and the environment.

The integration of BIM and AR enables professionals to interact both in the digital domain, where they can explore various layers of information, and in the physical environment, where they can engage with the 3D model at real scale on-site. This creates a more immediate and clear understanding of how the project will impact the physical space [12].

During the design phase, AR enhances collaboration between teams by allowing for the verification and analysis of the integration of various disciplines with the environment. Professionals can view the model directly at the future construction site, discuss changes or adjustments more intuitively [13]. This integration supports informed decision-making in the design process.

Mascareñas D. et al [10] highlights the use of AR in the creation of nuclear smart infrastructures. The AR-based prototype developed for simulated environments helps to anticipate problems and guide the development of real systems, enhancing project safety and efficiency. The use of AR not only speeds up decision-making but also has the potential to support the maintenance of high safety standards throughout all phases of the project, pending further validation in regulatory contexts.

2.3. Nuclear Licensing

The contribution of AR to nuclear licensing essentially stems from its primary applications in other areas related to the nuclear field, as mentioned in the previous topics. Thus, the AR applications cited, for example, in security and quality assurance, are directly related to or favor nuclear licensing.

Updates, expansions, and general changes in nuclear facilities can be better demonstrated, monitored, and documented by regulatory bodies using AR resources, facilitating the procedures for obtaining construction licenses. Independent technical oversight bodies can use AR in their verifications and inspections, allowing for immediate visualization of projects during construction and electromechanical assembly.

Emergency and evacuation procedures can be better implemented and even reformulated with the help of AR to create visual guides and pathways to orient personnel in case of incidents, including integrating instructions during simulations and training. Additionally, through the use of AR devices, it would be possible to display, as one walks through the facility, distinct markings and radiological classification regions, indicated by colors in the environment, for example. As a proposed application, further studies are required to confirm its practical effectiveness and validate its use within regulatory contexts.

2.4. Construction Phase

The application of AR enhances the planning of construction by allowing the visualization of 3D models directly integrated into the construction site. This capability allows for a more comprehensive understanding of the interactions between the physical environment and the various components of the construction, such as structures and systems [14]. However, most construction sites still rely on traditional processes. The application of AR solutions represents an underutilized potential, as 3D models used in these applications are often already produced during the design phase, but are not utilized after the generation of 2D documentation.

In the context of nuclear facility construction, which involve multiple teams and disciplines, AR enables the superimposition of detailed information onto the physical environment, thereby aiding in the identification of layout issues, facilitating early adjustments, and improving the coordination of activities. This integration enhances communication among teams, reduces errors and rework, and contributes to the successful adherence to project deadlines and budgets, ultimately increasing the overall efficacy of the project.

Among other specific applications, with AR arises the possibility of placing QR codes at strategic points on the construction site, enabling teams to instantly access the 3D model and view what is hidden behind walls or above ceilings without physical interventions. For example, if it is necessary to change the position of an specific equipment, AR can accurately identify the location of wall supports, pipes, and required connections, as well as ensuring that it will fit and if that change in possible, saving time and significantly reducing the impact on the project's schedule and budget.

In this context, AR facilitates the management of changes during construction - a critical aspect in long-duration projects like those in the nuclear industry - where technologies and processes may evolve over the years. With 3D models integrated into the physical environment, it is possible to quickly generate the "as-built" version at various stages of the project, allowing teams to integrate this information into the management process, ensuring that adjustments to be made more efficiently and accurately.

2.5. Operation

In the operational context, the integration of AR offers significant potential to enhance the accuracy and efficiency of operations by providing interactive 3D instructions, facilitating a better understanding of tasks. C. Botto et al [15] applied AR tools in manual assembly activities in industries, and resulted in a significant reduction in the number of errors, with only a slight increase in operation time. This increase is likely attributed to the time required for adaptation to the new technology. The addition of contextual information proved significant in preventing faults in complex processes.

Similarly, in the nuclear field, AR can provide precise overlay instructions on the real environment, both for operators situated in the control room and for technicians performing complex tasks (e.g. replacing items or refueling nuclear reactors). The use of AR devices in nuclear plants can reduce workers exposure to radiation [16], a constant concern in the operation of these facilities. AR can provide real-time data on radiation levels in different areas of the plant, allowing workers to make more informed and safer decisions. Furthermore, this technology can help avoid unplanned shutdowns, ensuring greater operational continuity.

AR not only facilitates operations but also can serve an important role in training operators and technicians in nuclear facilities through training and simulation of both operational and abnormal conditions. Additionally, it contributes to ergonomic improvements and human factors engineering, significantly enhancing the safety and effectiveness of operations. The application of AR can be extended to other phases of a project's lifecycle, providing ongoing support throughout the operation as well as decomissioning.

Beyond improving operational efficiency and safety, the use of AR in high-complexity scenarios demonstrates its role in adapting to new technological challenges, such as those encountered in the nuclear sector. Thus, AR can be utilized as a tool for modernizing operations, providing real-time support, enhancing safety and ensuring efficiency in an increasingly complex and technologically advanced environment, allowing the nuclear sector to continue innovating and improving its processes while maintaining its required safety levels.

2.6. Safeguards

In summary, international treaties on the non-proliferation of nuclear weapons prohibit signatory nations, which do not have such armaments, from developing them. To ensure conformity with these provisions, these nations are subject to inspections and visits by International Atomic Energy Agency (IAEA) inspectors at their nuclear facilities, with the aim of verifying the absence of undeclared nuclear materials and activities. Significant difficulties or issues are not expected in IAEA inspections of civil nuclear energy facilities. However, the high level of sensitive technological and industrial development associated with the military and defense aspects of facilities supporting nuclear-powered submarines makes these installations strategic for national sovereignty.

Currently, there are no clear definitions on how such inspections could be conducted in facilities with these characteristics. However, it is conjectured that safeguards activities must be limited to meet the requirements of regulatory authorities without exposing sensitive technologies and strategic defense applications [17 - 20].

Thus, it is necessary to develop special procedures and additional tools that help balance the IAEA inspection requirements, and the preservation of industrial secrecy of sensitive technologies, without compromising military and defense aspects. AR technology may offer innovative solutions to this challenge, and AR applications specifically aimed at safeguarding civil facilities are under study [21]. In addition to the previously mentioned applications, such as the use of QR codes for real-time information and instruction projections in the physical environment, there is also the possibility of insertion of virtual elements on top of real world elements, which would restrict the visibility of real items as well as whole rooms or areas. This approach could virtually limit the complete view of sensitive information from any position of the inspector if this solution is adopted.

2.7. Nuclear Security

AR can be used for the monitoring and surveillance of nuclear facilities by overlaying information from various sources onto surveillance camera images. This allows for the display of alerts, visitor identification (access control) or security anomalies in security operation centers. For field surveillance, this information can be made available through AR devices, facilitating the identification of threats and enabling a rapid and effective response.

In threat response actions, AR applications can be used to display maps (such as facility layouts, physical barrier positions etc.), routes, and signal paths over the physical environment. This provides visual guidelines and step-by-step instructions based on the current situation. The integration of real-time security information with the operator's view of the physical environment allows for a more efficient analysis of vulnerabilities and the planning of threat responses.

AR applications can also be envisioned for training and simulations of intrusions or other security scenarios, allowing personnel to train their response actions in a controlled and interactive environment with visual overlays of security procedures directly onto the physical environment chosen for the training/simulation. This approach enhances the understanding and retention of instructions. Additionally, it improves coordination and communication among involved agents by providing remote support to security personnel through AR technology.

Thus, with applications aimed at the physical protection of facilities, the use of AR enhances situational awareness by allowing the user to maintain a view of the physical environment for emergency actions while simultaneously receiving critical information and alerts in their field of vision. This real-time capability can occur in the field via AR devices or in security operation centers through monitoring systems (cameras and monitors). This versatility of AR can lead to more efficient detection and response actions in combating threats, as well as contribute to the training and coordination of overall physical protection measures in nuclear facilities [22].

2.8. Quality Assurance

In the nuclear sector, comformity and quality control are essential due to stringent safety requirements. Immersive technologies provide a range of additional resources for quality assurance (QA) across various stages of a project. In particular, according Fortuna, S. et al [23] augmented reality (AR) has proven highly effective in quality inspection, ensuring that products and processes comply with regulatory requirements.

During the design phases, AR can be used in alongside with Building Information Modeling (BIM) methodology to verify project documentation and the overall consistency of the project. For example, by visualizing a project's model, the information associated with each item can be linked to its virtual model, which can be easily accessed and manipulated by the user, providing a more visual and intuitive experience.

Traditional quality control processes typically use paper instructions to guide inspectors through various procedures. These procedures require correlating paper instructions with actions performed on real objects, often without additional guidance, resulting in more time-consuming inspections and a significant probability of errors due to the dispersion of attention between instructions and the task at hand [24].

In this context, the use of AR represents a significant technological opportunity to enhance task more efficiency, keeping the inspector focused on the task while receiving visual instructions directly in the physical environment where the task is performed. AR allows for the display of contextualized digital information about the real world or its representation, which can be potentially useful for quality control processes with step-by-step instructions or other supplemental data. Furthermore, AR can reduce operational costs by improving spatial awareness and decreasing errors and time [25]. The use of AR can facilitate inspections and audits required by the quality assurance program at all stages of a project, both by enabling the overlay of critical information and inspection points directly onto physical installations, and by allowing the creation of more detailed and comprehensible reports, with records of notes and images directly on the models of the installations.

In the manufacturing processes for the nuclear industry, AR enables real-time visual inspections by overlaying virtual models with real items, facilitating the detection of defects or imperfections. Such applications are also valuable for inspecting nuclear plant components during maintenance and refueling shutdowns, improving inspection efficiency and ensuring that all steps are followed accurately.

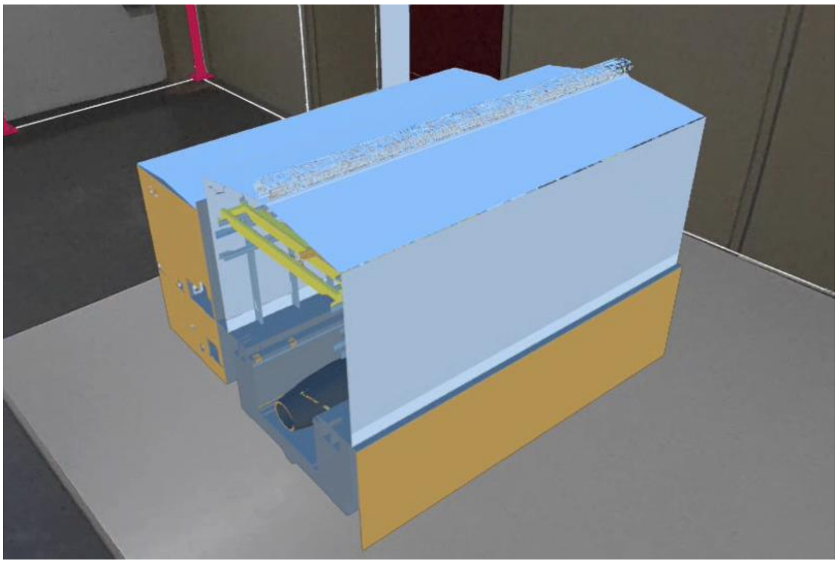
Companies are already exploring the use of AR in quality inspection in nuclear environments, developing interactive instructions that guide workers to follow specific steps during the inspection and maintenance of critical reactor components. This approach has proven effective in improving process quality, reducing accidents, and increasing inspection efficiency [25].

3. RESULTS AND DISCUSSIONS

By using the methodology and steps previously described, it was possible to develop two cases for the AR application (Demonstration and Exhibition): a virtual model of the CME project (Figure 2) and virtual installations in the physical environment (Figure 3). This initial application, utilizing current concepts and implemented in a nuclear facility, allows for the verification of the functionality and compatibility of the software and procedures used for generating 3D models and their composition with environmental images. Thus, the outcome of this initial work will enable the development of solutions addressing issues specifically encountered in facilities with the purpose of the Specialized Maintenance Complex (CME).

These preliminary tests were implemented in a simulated environment, without yet involving a real facility or field operational validation. The applications described herein represent a conceptual proposal based on project experience and technical references, requiring further steps for formal validation.

Figure 2: simplified digital model of a land-based support facility for nuclear-powered submarines



Source: authors

Figure 3: set of pipes, ducts and fire-fighting system, designed to integrate into the reference room

Source: authors

In both cases, the model was visualized through AR by professionals involved in the project's development, as well as those participating in the decision-making process. The use of this technology provided advantages in the interaction between these professionals and the project, enhancing their perception and interaction with visual information. Despite the preliminary tests, it was already possible to observe in the analyzed cases that AR facilitates communication among the various professionals involved, promoting a more dynamic exchange of information. Furthermore, it enabled a visual perception of the project that went beyond the limitations of the BIM model, establishing itself as a highly useful complementary tool in the design process.

According to the representation in Figure 3, AR emerged as a valuable tool for project coordination. The visualization in the real environment supported a more comprehensive assessment of the impact of installations on the overall project. Furthermore, AR enabled professionals to identify points of conflict (clashes), such as interferences between piping systems and between fire sprinkler piping and the newly proposed air conditioning system, which had not yet been incorporated into the BIM model.

Concerning the export of the BIM model to the AR device, advantages and limitations were identified in aspects such as accuracy, scale, processing time, texture and quality. In both cases analyzed, the exportation process was simple, maintaining the dimensions and scale of the BIM model. This ensured the precise placement of installations within the real-world environment, as illustrated in Figure 3.

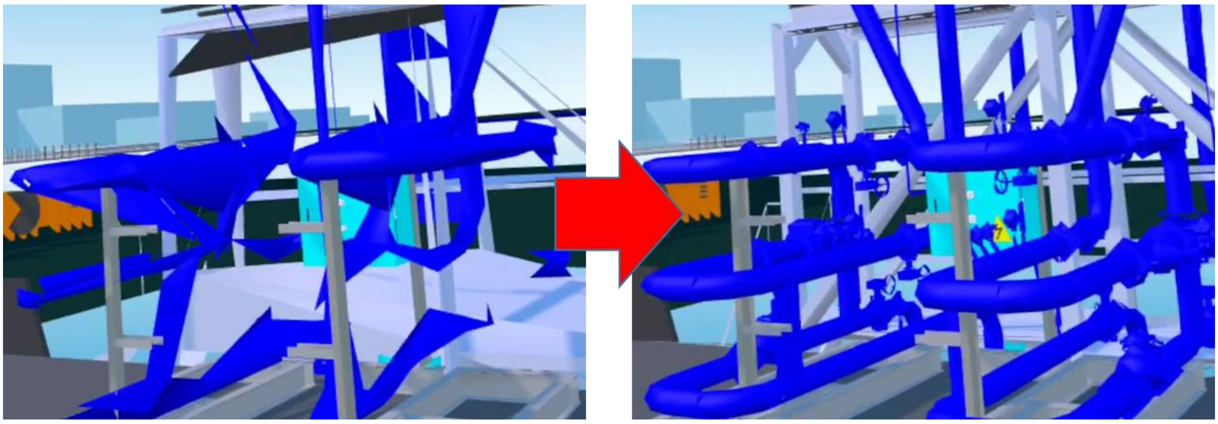
However, the export was carried out only for a specific part of the CME project and simple installations of a room, making it necessary to advance the research to evaluate the application of AR across the entire nuclear infrastructure. To ensure the effectiveness of the process, it is imperative to map the workflow management between BIM and AR, as well as assess the suitability of the software, hardware, and devices, in order to meet the future requirements of the project.

In this regard, it is worth noting that the AR glasses used are a basic version intended for domestic use, not a developer or industrial-grade model. As such, the memory, processing capacity, and the way the software manages these resources allow for the import of files with a maximum size of 800 MB. In the case of more complex digital models, visualization difficulties arise, such as (see Figure 4 and Figure 5):

- ✓ Blurring or incomplete image: the rendering may display an "incomplete" model or low-resolution textures while the data is still being processed. This can be seen as a blurred image or one missing details.
- ✓ Gradual loading: depending on the file size and model complexity, the rendering process may occur progressively, with image quality improving as the device loads more data. During this period, the image may appear in a "basic" version until it is fully rendered with all its details.
- ✓ Temporary failures: in some cases, if the file is too large or the device’s performance is affected, the model may exhibit failures such as visual glitches, where certain parts of the image are not rendered correctly.

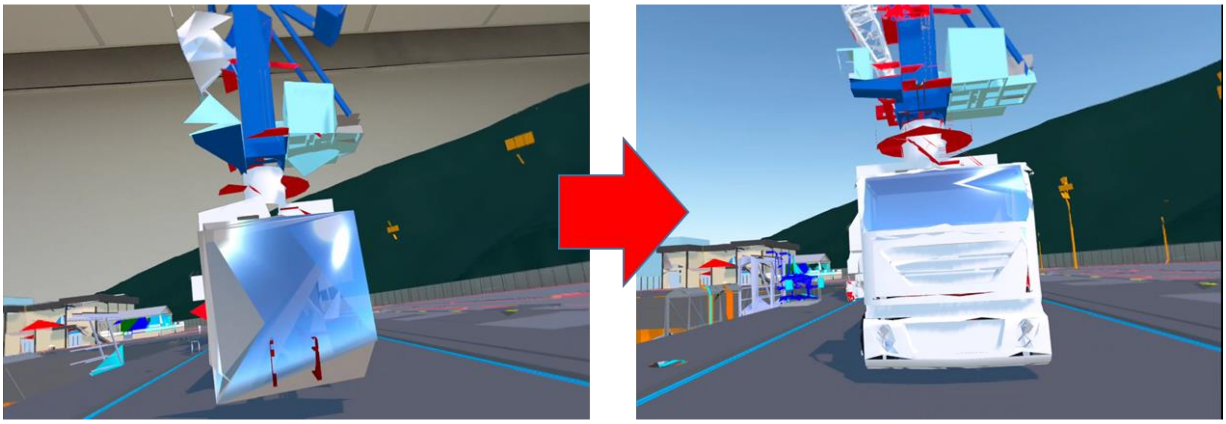
- ✓ Texture timing: if the model or scene contains heavy textures, they may take longer to load and apply correctly, causing the model to appear roughly sketched or with low-resolution textures until everything is fully rendered.

Figure 4: visualization difficulties



Source: authors

Figure 5: visualization difficulties



Source: authors

Another important aspect to consider is the textures when exporting the BIM model to AR. The AR device used its own textures, and when importing the model, adjustments must be made for compatibility. In general, the textures provided by the AR device are of lower quality than those in the BIM model, which may impact the visual accuracy and user experience.

In general, areas with immediate application of AR technologies tend to have a significant interface with and aspects related to human factors engineering. However, the integration of AR must consider visual distraction, information overload, and user comfort, ensuring that the technology enhances human performance without compromising safety and effectiveness.

Despite the demonstrated benefits, the integration of AR and other immersive technologies in the nuclear sector will likely face specific challenges, reflecting the conservatism in the use of traditional tools and solutions. Adapting existing processes in nuclear facilities is complex and requires not only restructuring workflows but also ensuring rigorously that the new technologies will not compromise operational safety. Furthermore, qualifying employees to operate these technologies safely is crucial, necessitating specialized training and cultural changes within organizations.

One of the greatest obstacles in the nuclear sector is the concern for the safety and reliability of immersive systems. AR, for instance, can affect the visual perception of operators in highly complex environments. To address these challenges, companies have been collaborating to develop customized AR solutions, focused on enhancing safety and efficiency in nuclear reactor inspections. These solutions include improvements in AR devices, ensuring that operators have clear and accurate visibility even in hard-to-reach areas or in low-light conditions.

Ultimately, based on the conceptual analysis conducted, Table 2 presents a preliminary qualitative comparison between traditional practices and Augmented Reality (AR)-supported approaches across the different phases of a project. This comparison is grounded in expectations and theoretical indications drawn from specialized literature and practical observations, and does not yet constitute validated empirical evidence. The aim is to provide an initial perspective on the potential benefits and limitations of AR, supporting the formulation of future research directions and hypotheses for subsequent studies.

Table 2: Expected qualitative contrasts between conventional and AR-enhanced methods

Project Phase	Evaluated Metric	Traditional Techniques	Augmented Reality (AR)	AR Advantage
Conceptual Design	Spatial clash detection	Manual review of documents and 3D models	Interactive in simulated field	Time reduction
	Level of multidisciplinary understanding	Technical reading and constant meetings	Immersive and intuitive visualization for all stakeholders	Better team communication
Executive Design	Technical review	Partial review	High – AR enables full-scale review	Higher technical reliability
	Agility in applying modifications	Slow – requires CAD adjustments and new review cycle	Fast – changes visualized in real-time in the model	More agile iterations
Construction Phase	Rework due to design errors	High – 10 to 25% of construction time may be rework	Low – AR helps anticipate and prevent errors	Rework reduction
	Alignment between project and execution (as-built)	Manual inspections and document comparisons	On-site direct visualization with AR in real-time	Precise synchronization
Commissioning	Validation time of installed systems	Days to weeks, with checklists and physical inspections	Hours – with virtual overlay of expected systems	Process acceleration
	Compliance documentation	Manual	Automated and integrated into digital model	Enhanced reliability and traceability

3.1. Study Limitations, Future Scope, and Technical and Regulatory Challenges

This work is qualitative and exploratory in nature, aiming to present the potential of Augmented Reality (AR) in nuclear support facilities for submarines. No formal quantitative metrics were applied in this study, as the focus is on demonstrating usage possibilities rather than validating hypotheses. Future investigations may include data such as time saved, number of detected interferences, or performance comparisons with traditional methods.

The adoption of Augmented Reality in regulated environments such as nuclear facilities faces significant challenges. These include the technical validation of digital solutions, the need for specific certifications to ensure operational safety, and the adaptation of existing regulations to new technologies. These aspects should be further explored in future research and field testing.

4. CONCLUSIONS

As a preliminary approach to implementing Augmented Reality (AR) technology in design and operation of land support facilities for nuclear-powered submarines, this study validated the methodology, integration, and functionality of the proposed arrangement for incorporating the 3D model into the physical environment using an application on AR smart glasses for visualization. In one of the applications - the CME project - being developed by the Brazilian Navy, was used as a reference to create a simplified model of the facility and its scaled projection as a mock-up integrated into the physical environment, providing an immersive experience with simple and intuitive interaction. This approach allowed the assessment of the compatibility and functionality of the arrangement in terms of items, software, and procedures. Subsequently, in alignment with the objectives and unique characteristics of this facility, various potential applications of AR were identified. These applications could lead to significant enhancements in nuclear quality, scheduling, and various aspects of the design, construction, licensing, and operation phases of this specific undertaking. Thus, the utilization of AR in the CME project, and others nuclear installations, is viewed as an opportunity to provide solutions aligned with the high level of technological development required for its realization, facilitating a deeper understanding and more effective interaction with the complexities involved. The successful integration of the models not only met the initial objectives but also opened up new possibilities for the application of these technologies in future projects. In addition to this application, other possibilities for using Augmented Reality (AR) resources in the design of land support facilities for nuclear-powered submarines have been proposed. As a proposed application, further studies are required to confirm its practical effectiveness and validate its use within regulatory contexts.

ACKNOWLEDGMENT

Authors would like to acknowledge the Diretoria de Desenvolvimento Nuclear da Marinha (DDNM), Coordenadoria-Geral do Programa de Desenvolvimento de Submarino com Propulsão Nuclear (COGESN), Amazônia Azul Tecnologias de Defesa S.A. (AMAZUL), and the Fundação para o Desenvolvimento Tecnológico da Engenharia (FDTE).

CONFLICT OF INTEREST

All authors declare that they have no conflicts of interest.

REFERENCES

[1] Stephanie Overby. Augmented Reality (AR): 4 enterprise use cases – What are companies doing with augmented reality? Available at: https://enterprisersproject.com/article/2019/10/ar-augmented-reality-4-use-cases Acessed on: 9 Aug. 2024.

[2] Baroni, D. B., Borsoi, S. S., Mattar Neto, M., Oliveira, P. S. P., & Maturana, M. C. (2022). Licensing Approach Applicable to Land Facilities Supporting Nuclear-Powered

Submarines. Brazilian Journal of Radiation Sciences, 10(3A (Suppl.). Available at: https://doi.org/10.15392/2319-0612.2022.2083. Acessed on: 10 Fev. 2024.

[3] M. A. Talrico, P. F. Frutuoso e Melo. Considerations About The Licensing Process of Special Nuclear Industrial Facilities. 2015. International Nuclear Atlantic Conference - INAC, 2015.

[4] Malcolm Smith. The D154 Project - Redevelopment of the Submarine Support Facilities at Devonport Royal Dockyard. Available at: https://www.ingenia.org.uk/getattachment/50b6ddf0-8f43-4e14-b3b5-b26bdf551ef4/Smith.pdf. Acessed on: 10 Fev. 2024.

[5] C. Marriot, P. Bate. Dependent Failure Assessment in the Development of a Defuelling Facility for Nuclear Submarines. 5th IET International Conference on System Safety 2010.

[6] Carmigniani, J., Furht, B., Anisetti, M. et al. Augmented reality technologies, systems and applications. Multimed Tools Appl 51, 341–377 (2011). Available at: https://doi.org/10.1007/s11042-010-0660-6. Acessed on: 15 Fev. 2024.

[7] Arena, F.; Collotta, M.; Pau, G.; Termine, F. An Overview of Augmented Reality. Computers 2022. Available on: https://doi.org/10.3390/computers11020028. Acessed at: 15 Fev. 2024.

[8] Sarmento, M. F.; Farias Segundo, M. B. Desenho arquitetônico com BIM e Realidade Aumentada na Engenharia Civil. Encontro Nacional Sobre o Ensino de BIM, 2023. Porto Alegre. p. 1–1. Available at: https://eventos.antac.org.br/index.php/enebim/article/view/3399. Acessed on: 15 Fev. 2024.

[9] Introdução de Realidade Aumentada para Aplicação de Treinamento em Radioproteção e Dosimetria na Área Acadêmica do IRD". Available at: https://inis.iaea.org/collection/NCLCollectionStore/_Public/49/025/49025707.pdf. Acessed on: 20 Fev. 2024.

[10] Mascareñas D. et al, Augmented Reality for Enabling Smart Nuclear Infrastructure. Front. Built Environ. 5:82. 2019. doi: 10.3389/fbuil.2019.00082. Available at: https://www.frontiersin.org/journals/built-environment/articles/10.3389/fbuil.2019.00082 Acessed on: 18 Fev. 2024.

[11] Pakarinen Satu, Laarni Jari, Koskinen Hanna, Passi Tomi, Liinasuo Marja, Salonen Tuisku-Tuuli, Virtual-Reality training solutions for nuclear power plant field operators: A

scoping review, Progress in Nuclear Energy, Volume 169, 2024, 105104, ISSN 0149-1970, Available at: https://doi.org/10.1016/j.pnucene.2024.105104 Acessed on: 20 Fev. 2024.

[12] Arowoiya, V. A., Oke, A. E., Akanni, P. O., Kwofie, T. E., & Enih, P. I. (2023). Augmented reality for construction revolution–analysis of critical success factors. International journal of construction management, 23(11), 1867-1874.

[13] Nassereddine, H., Veeramani, D., & Hanna, A. S. (2022). Design, development, and validation of an augmented reality-enabled production strategy process. Frontiers in Built Environment, 8, 730098.

[14] Safikhani, S., Keller, S., Schweiger, G., & Pirker, J. (2022). Immersive virtual reality for extending the potential of building information modeling in architecture, engineering, and construction sector: systematic review. International Journal of Digital Earth, 15(1), 503-526.

[15] C. Botto et al. Augmented Reality for the Manufacturing Industry: The Case of an Assembly Assistant. 2020 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW), Atlanta, GA, USA, 2020, pp. 299-304.

[16] Deloitte. Augmented reality applications In nuclear power plants. Available at: https://www2.deloitte.com/content/dam/Deloitte/us/Documents/process-and-operations/us-cons-augmented-reality-applications-in-nuclear-power-plants.pdf Acessed on: 02 Aug. 2024.

[17] Sébastien Philippe – "Safeguarding the Military Naval Nuclear Fuel Cycle". Journal of Nuclear Materials Management. Spring 2014 Volume XLII, No. 3.

[18] Eugenio Pacelli Lazzarotti Diniz Costa - "Brazil's Nuclear Submarine: A Broader Approach to the Safeguards Issue". Rev. Bras. Polít. Int., 60(2): e005, 2017.

[19] Sébastien Philippe – "All at Sea? A Safeguards Approach for the Military Naval Nuclear Fuel Cycle".

[20] Laura Rockwood – "Naval Nuclear Propulsion and IAEA Safeguards". Federation of American Scientists, August 2017.

[21] Westphal G, Garner J, McGirl N. Leveraging Industrial Mixed Reality Sucesses for Safeguards. Proceedings of the INMM & ESARDA Joint Virtual Annual Meeting, 2021. Available at: https://www.osti.gov/servlets/purl/1836444 Acessed on: 12 Aug. 2024.

[22] Augmented Reality: The Real Deal in Security. ONCAM. Available at: https://blog.oncamgrandeye.com/featured/augmented-reality-the-real-deal-in-security Acessed on: 8 Jul. 2024.

[23] Fortuna, S. et al. (2024). A comparative study of Augmented Reality rendering techniques for industrial assembly inspection. Computers in Industry, 155, 104057.

[24] Alves, J.B., Marques, B., Dias, P. et al. Using augmented reality for industrial quality assurance: a shop floor user study. Int J Adv Manuf Technol 115, 105–116 (2021). Available at: https://link.springer.com/article/10.1007/s00170-021-07049-8 Acessed on: 12 Aug. 2024.

[25] Hiren Kanani. Augmented Reality for Quality Inspection: A Comprehensive Overview. Plutomen, 2024. Available at: https://pluto-men.com/augmented-reality-for-quality-inspection/ Acessed on: 12 Aug. 2024.

LICENSE