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► To cite this version:

Caroline Chabal, Thibaud Durand, Hamza Helaaazri, Julien Delrieu, Michaël Gauthier, et al.. Developing digital twins to assist in the control of nuclear complex processes. NiDS 2024 - 4th International Conference on Novel & Intelligent Digital Systems, Sep 2024, Athènes, Greece. cea-04720676

HAL Id: cea-04720676

<https://cea.hal.science/cea-04720676v1>

Submitted on 3 Oct 2024

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Developing Digital Twins to Assist in the Control of Nuclear Complex Processes

Caroline Chabal¹[0000-0002-6958-2542], Thibaud Durand¹[0009-0009-7269-2417], Hamza Belaazri¹[0009-0002-3880-3135], Julien Delrieu¹, Michael Gauthier¹, Alain Ledoux¹, Christian Pèrè²

¹ French Alternative Energies and Atomic Energy Commission (CEA), DES, ISEC, DPME, Univ. Montpellier, Marcoule –France

² GAMBI-M, 30200 Bagnols sur Cèze, France
caroline.chabal@cea.fr

Abstract. The current emergence of new digital technologies is opening up new prospects for industry, making production more efficient, safer, more flexible and more reliable than ever. Building on initiatives already carried out in various sectors, the application of these technologies to the operation of vitrification processes could make it possible to improve knowledge of processes, optimize their operation, train operators, help with predictive maintenance and assist with process control.

The SOSIE project is a collaborative innovative project, which aims at providing an initial proof of concept for the implementation of digital technologies integrating Virtual Reality, Augmented Reality, and Artificial Intelligence.

This paper presents the first developments realized in the project, where three kinds of digital twins have been developed on two complementary vitrification processes: first, the “visual” digital twin, based on an immersive and interactive application from reverse-built 3D models, secondly, the “augmented” digital twin, which connects the visual twin to the supervisory PLC and provides real-time feedback of supervisory information, and thirdly, the “intelligent” digital twin, exploiting databases from operations to train Machine-Learning algorithms and helping predict breakdowns and process drifts.

Keywords: vitrification process, digital twin, Augmented Reality, Machine Learning.

1 Introduction

In industry, the hostile nature of environments can result from various causes: extreme temperatures or pressures, chemical, biological or radioactive aggression. In the nuclear industry, the hostile nature of environments is mainly due to radiological stress, and the challenge of operations is to protect operators. For decades, the CEA has been working on the development of vitrification processes [1], which enable the most radioactive waste to be packaged. The waste is incorporated and immobilized in a durable

glass matrix, before being packaged and stored while awaiting a disposal site. The implementation and operation of these vitrification processes is complex, requiring highly specialized laboratories equipped with shielded chambers.

The current emergence of new digital technologies is opening up new prospects for the operation of these vitrification processes. Big data, Artificial Intelligence (AI), the Internet of Things, Augmented Reality...: new technologies are bringing new life to all sectors of Industry 4.0. Their growing footprint is fostering the emergence of new business models, new ways of producing, working, exploiting available data, being more efficient, while reducing operational costs. Among these emerging technologies, the Digital Twin (DT) [2] aims at developing a digital replica of an object, process or system... This digital double appropriates all the components of its physical twin, as well as its properties. It is based on a model of the system to be digitized, including connected sensors that measure the system's physical parameters in real-time, and AI algorithms that analyze a very large database, derived from historical data on the process past usage. These algorithms model the system's dynamic behavior and can predict the outcome.

This article describes the developments carried out as part of the SOSIE project, which aims to build DTs of vitrification processes. After a brief review of the state of the art, the article will describe the SOSIE project, its objectives and challenges. It will then present the works that have already been carried out, focusing on the three stages of the project, namely the development of the visual, augmented and intelligent DT. Finally, the outlook for the future will be discussed.

2 State of the Art

The state of the art shows that the use of DTs in the industrial sector is booming. The aerospace [3], aeronautics [4], and defense sectors were the first to explore their potential. In aeronautics, it can be used to simulate aircraft physics, monitor system operation and ensure crew safety [5]. In the construction sector, it can be applied to monitor the evolution [6] of a building within its environment and to assess the extent of work needed, as well as potential future safety issues. In the automotive industry, it contributes to vehicle safety [7] by controlling the quality of parts. Renault has implemented the DT to optimize the production of its electric motors by digitizing their production chain [8].

In the energy sector, the DT is implemented in wind farms [9], where in situ sensor data informs of production drifts, and therefore of equipment malfunctions. In the nuclear sector, EDF Digital Reactor project [10] is a large-scale research and development project involving all the major players in the French nuclear industry. Its aim is to create a DT of a nuclear reactor that will make it possible to virtually immerse oneself in the operation of a reactor, carry out ultra-realistic simulation studies, train all operators and promote the French nuclear industry's calculation codes and knowledge to foreign nuclear operators. Few developments of DTs applied to nuclear processes are yet available, and SOSIE's results will be a first in this field.

3 The SOSIE Project

Co-funded by the Occitanie region, the SOSIE project (June 2022-December 2024) is an innovation project, resulting from a collaboration between the CEA and GAMBIM. In line with this trend to initiate a digital transition on complex processes, the project aims at declining the DT on vitrification processes. The approach developed will be able to provide a digital mock-up of the process, integrating all the relevant data for operation first and then building a predictive model of process behaviour, thus identifying weak signals and anticipating failures or breakdowns.

The objective therefore consists of implementing all these digital technologies on two case studies in Marcoule (Bagnols sur Cèze, France), two complementary vitrification processes: the first is a cold process (without radioactivity), called ELVIS (see Fig. 1), and the second, called VESPA (see Fig. 2), is a production process implemented in a shielded cell.



Fig. 1. ELVIS vitrification process



Fig. 2. VESPA vitrification process located in the shielded cell

The SOSIE project aims at developing on the two case studies identified:

- The “visual” DT, based on reverse-built 3D models, in order to implement an immersive and interactive simulation, capable of being used on a Virtual Reality (VR) headset and on Augmented Reality (AR) glasses.
- The “augmented” DT, which connects the visual DT to the supervisory PLC and provides real-time feedback of supervisory information.
- The “intelligent” DT, exploiting databases from operations to train Machine-Learning algorithms, to analyse weak signals and help predict breakdowns and process drifts.

In the SOSIE project, proofs of concept are expected on the operability, usability and contribution of digital technologies to complex processes, in particular in order to capitalize on process knowledge; prepare operations; train operators in a more intuitive and ergonomic way, assist process control during operations; and assist predictive maintenance.

4 First results

4.1 Development of the “visual” DT

The first step of the project consists in building the 3D model of the complete work environments. In fact, the processes involved in the study on are quite old processes and the plans we had were not necessarily up to date. The 3D reverse engineering work consisted of doing lasergrammetry, using a 3D laser scanner to scan the space using a laser beam (360° horizontally and 305° vertically), in order to obtain a discrete representation (point cloud) of the real environment.

This investigation was achieved with a FARO type scanner [11] in two stages: a first scanning was taken on ELVIS. The second survey on VESPA was much more complex to be implemented, given that it took place in a nuclear environment without direct access. The implementation of the scanner was carried out using remote manipulators, located in the shielded cell. The scanning operations gave robust point clouds that have been used to reconstruct the 3D model (see Fig.3).



Fig. 3. ELVIS (left) point clouds

From these point clouds, the construction of the 3D model has been manual, and focused on building object-by-object, using also available photos and technical documents. This work required several weeks for each process and made it possible to reconstruct around 90% of the objects from each process in 3D. For instance, for ELVIS platform, around 400 3D objects have been designed, only the flexible (deformable) elements were not modelled.

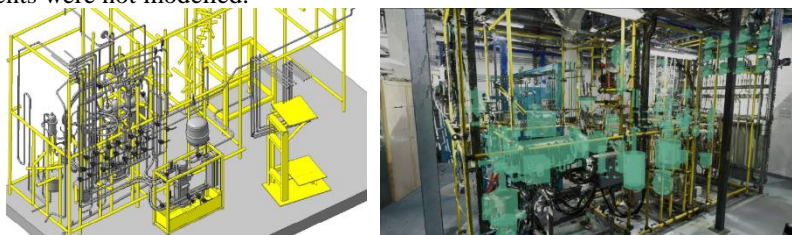


Fig. 4. ELVIS 3D Model (left) and 3D objects superimposed on ELVIS process (right)

From these 3D models (see Fig.4), developments have made them compatible with AR, which makes it possible, thanks to Holographic glasses [12] to see the “inside” of the equipment through a system of co-location of information. Digital information is added on the “real” environment (see Fig.4).

4.2 Development of the “augmented” DT

The next step in the project was to build on the visual DT developed earlier, by filling in all the metadata linked to the process, such as references, builder data, material, mass... linked to the objects, as well as drawings, assembly or maintenance procedures. A digital database has been built to match the objects with the metadata. All this data can be accessed via the application with a simple finger pinch (see Fig.5).



Fig.5. Example of user rendering: 2D plan (left) procedure (middle) and sensor graph (right)

Then the developments consisted in enriching the visual DT with information from the field. This was done by coupling the visual DT to the process control PLC. For the two processes studied, the supervisor architectures are different. The work was carried out on the ELVIS supervisor, which uses specific supervisory software. Read-only access to the data contained in this database has been developed, and is rendered in the AR application in the form of a dashboard, via a communication protocol designed specifically between the acquisition card and a data server dedicated.

The coupling involved reading the information and rendering it in the virtual scene. Several types of display have been developed: display of instantaneous values in text form or display of graphs showing the evolution of the measurement (see Fig.5). The implemented link is real-time, providing information on the current status of all process sensors (temperature, pressure, flow, volume, level) at any time. This work needs to be carried out for the VESPA platform, where access to supervisor data is different and presents greater implementation constraints.

4.3 Development of the “intelligent” DT

In the final phase of the project, the intelligent DT of the two processes studied is being developed. By intelligent DT, we mean using Artificial Intelligence (AI) algorithms to help diagnose the state of the process. ELVIS and VESPA, in operation for several years, own data recorded from in situ sensors, providing a potential learning database.

The integration of advanced AI techniques, in particular Deep Learning algorithms, marks a paradigm shift in industrial monitoring and control systems [13]. By employing sophisticated autoencoder models [14], it is possible to detect abnormal behaviours in sensor data streams in real-time. Anomalies, i.e. deviations from normal operations, are identified when the reconstructed output deviates significantly from the original input. This methodology enables early detection of irregularities, such as equipment malfunctions or process deviations, which could potentially compromise operational safety or

product integrity. By swiftly pinpointing anomalies in real-time, autoencoders empower operators to take timely corrective actions. Over the past six months, much of the development has been focused on collecting, cleaning, simplifying and standardising the data. The first step of data processing is to collect data from the automated systems, capturing raw information from various sensors and sources. Following this initial data acquisition phase, it has become evident that the structure and format of the data were not suitable for a Data Science project. The files exhibit heterogeneity in form and are intermixed with other non-data files. Consequently, prior to the cleaning phase, a crucial step of data integration has been necessary. This integration process is pivotal for seamlessly merging disparate datasets into a unified format. It involves a meticulous series of steps aimed at harmonizing and consolidating the collected data.

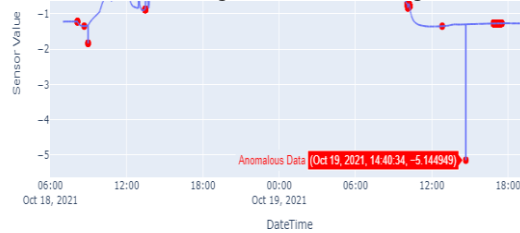


Fig. 6. First application of Autoencoder to detect anomalies in temperature sensor data

Upon completion of the integration process, the cleaning stage executes essential steps, encompassing the conversion of sensor values to numeric format, removal of duplicate rows, pruning of constant columns, resolution of duplicated sensor columns, management of missing sensors and values, categorization of sensors and commands, and systematic organization of columns. Following the preprocessing phase, an exploratory data analysis has been conducted to gain insights into the dataset's characteristics and relationships. This work is still in progress. First application of Autoencoders has been done (see Fig.6). The models will be optimized in the future months.

The SOSIE project also implements pre-trained computer vision algorithms, such as YOLO (You Only Look Once) [15], for efficient and accurate object detection within complex industrial workflows. Leveraging the principles of transfer learning, YOLO is adapted to the specific object detection requirements of industrial environments by fine-tuning it on a dataset tailored to the objects of interest. This approach capitalizes on the knowledge encoded within the pre-trained YOLO model, enhancing its ability to detect objects relevant to industrial processes.



Fig. 7. Object and key point detection of valves using YOLO

Additionally, techniques for detecting key points of objects have been used, providing valuable insights into object situations and conditions. For instance, in the case of

valves, key points may indicate whether the valve is open or closed, providing critical information for process monitoring and optimization (see Fig.7).

5 Limits and perspectives

One of the biggest limitations of these developments lies in the acceptability of the tool by end-users. The application made available to end users, non-experts in digital technologies, must be easy to use, sufficiently robust, and demonstrate benefit compared to current practices. To make the application as user-friendly as possible, end-users have been involved right from the start of the project: requirements specifications have been drawn up based on interviews with operators in the field to identify areas for improvement that would make their task easier. Developments have been thus targeted on specific procedures, where problems often occurred. Efforts have been made in the design of the user experience. An iterative approach has been adopted to test developments with a few users to validate the chosen ergonomics. A qualification campaign is planned over the next few months, involving around twenty beta-testers with very diverse profiles. They will all undergo training to learn how to use AR equipment correctly before the tests. Their feedback will be collected through questionnaires, and evaluated according to criteria such as efficiency, achievement of planned result, consumption of minimum resources (effort, time) and satisfaction (using ISO 9241 standard).

The other major task is to roll out developments on the VESPA process. The developments already done are intended to be scalable and generalizable. The software and hardware architecture of the DT has been designed to be deployed as easily as possible on other processes. The data structure, hierarchy and database architecture will make it possible to address any type of process, of any size. All development done on ELVIS has been reused for VESPA application. But the nuclear environment will potentially bring new constraints: the process is located in a shielded chain, and the use of devices such as HoloLens may be more restricted. Direct vision is very limited, possible only from portholes, and inner equipment is handled with remote handling arms. All the ergonomics need to be rethought to make the application usable. This work remains a challenge to be faced. In this nuclear environment, additional aspects relating to safety (risk of falling because of the HoloLens), cybersecurity (connection to PLCs) and connectivity (deployment of wireless solutions) are still to be discussed. Nevertheless, all these developments, in particular those linked to the use of predictive algorithms, should enable a significant gain in safety through the use of DT that detect weak signals and enable incidents to be avoided as early as possible.

6 Conclusion

This article presented the first developments carried out within the framework of the SOSIE project, aiming at developing DTs for complex processes in a nuclear environment. The work being carried out is based on the use of AR, VR and AI to develop a pilot assistance application. This article presents the initial developments carried out as part of the SOSIE project. The aim is to develop proofs of concept for DTs applied to

complex processes in a nuclear environment. The work carried out is based on the use of AR, VR and AI to develop a pilot assistance application.

The initial developments consisted of reconstructing 3D models of the process environments studied first and then building visual, augmented and intelligent DTs. Initial applications have been developed, combining augmented reality driving assistance and anomaly prediction algorithms.

The next stage is to qualify the application by having it tested by end users to assess its ergonomics and usability. The initial feedback is very promising, opening up new prospects for the use of digital technologies in the control of complex processes in the nuclear field.

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